

Alcoa 2-63-39

cy 3

ARC STABILITY AND MELTING
CHARACTERISTICS OF WELDING WIRE
FOR USE WITH 2219 ALUMINUM
ALLOY PLATE

PROPERTY OF
TECHNICAL LIBRARY
BY
J.H. DUDAS MS-IPL

Contract No. NAS8-5132
Task Order M-ME-TLA-AL-2

November 30, 1963
Report 2-63-39

Signed: J. H. Dudas
J.H. Dudas, Joining Section
Process Metallurgy Division

Approved: Allen S. Russell
Allen S. Russell, Chief
Process Metallurgy Division

JHD:mj

TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	1
INTRODUCTION	2
MATERIALS AND EQUIPMENT.	2
TEST PROCEDURES.	3-5
Arc Characteristics	3
Weld Cracking	4
Mechanical Tests.	4
Corrosion Resistance.	5
PRELIMINARY RESULTS.	5-11
Melting characteristics of Aluminum Electrodes.	5
Arc Stability - 5556 vs 2319 Electrodes	8
Arc Stability - 1100, 2014, 4043, and 4145 Electrodes.	9
Effect of Shielding Gas	10
Electrode Microstructure.	11
DISCUSSION OF PRELIMINARY RESULTS.	12
PROPOSED PROGRAM	15
PROGRAM RESULTS.	
Heat Treated 2319 Electrode	15
Modified 2319 Type Alloys - Cu, Si, and Be.	16
Arc Stability and Melting Characteristics.	17
Weld Mechanical Properties	17
Predicted Corrosion Behavior	18
Electroplated 2319 Electrode - Zn and Cd.	20
Arc Stability and Melting Characteristics.	20
Modified 2319 Type Alloys - Zn, Cd, Mg, Ca, Zr, and V.	22
Arc Stability and Melting Characteristics.	22
Weld Cracking.	23
Weld Mechanical Properties	24
Predicted Corrosion Behavior	25
Metal Fume Toxicity.	25
Characteristics of 2319 + Zn Electrodes	26
Horizontal Position Welds.	27
Shielding Gas Composition.	27
Power Supply Characteristics	28
CONCLUSIONS.	28
RECOMMENDATIONS FOR FUTURE WORK.	29
REFERENCES	29

TABLE OF CONTENTS (Cont'd.)

	<u>Page No.</u>
TABLE I - Compositions and Tensile Properties of 1/16-in. dia. Al Alloy Electrodes.	31
TABLE II - Selected Physical Properties that Influence Welding Characteristics	33
TABLE III - Properties of MIG Welds in 1/2-in. 2219-T87 Plate with 1/16-in. dia. Experimental 2319 Type Electrodes.	34
TABLE IV - Coating Thicknesses for 1/16-in. dia. 2319 Electrode Electroplated with Zinc and Cadmium.	35
TABLE V - Surface Resistance Values for Plated and Bare 2319 Electrode.	35
TABLE VI - Weld Crack Sensitivity of 2319 Type Welding Electrodes with 2219 Plate.	36
TABLE VII - Properties of MIG Welds in 1/2-in. 2219-T87 Plate with 1/16-in. dia. Experimental 2319 Type Electrodes.	37
Figure 1 - Welding Setup for Examining Arc Characteristics of Al Electrodes.	38
Figure 2 - Alcoa T-Joint Weld Cracking Specimen.	39
Figure 3 - Weld Tensile Test Specimens	40
Figure 4 - Melt-Off Rates for 1/16 in. dia. Standard Al Electrodes.	41
Figure 5 - Metal Transfer Characteristics for 1/16-in. dia. Standard Al Electrodes (Alloys 2319, 1100, 5556, 2014, 4043 and 4145)	42
Figure 6 - Arc Stability for 1/16-in. dia. 2319 and 5556 Electrodes	43
Figure 7 - Photograph of Weld Beads Deposited with 2319 and 5556 Electrodes.	44
Figure 8 - Arc Stability for 1/16-in. dia 2319, 1100, 4043, 4145, 2014, and 5556 Electrodes	45
Figure 9 - Photograph of Weld Beads Deposited by 2319, 1100, 5556, 2014, 4043, and 4145 Electrodes	46
Figure 10 - Arc Stability for 1/16-in. dia. 2319 and 5556 Electrodes with 100% Ar and 65% He-35% Ar Shielding Gas.	47

TABLE OF CONTENTS (Cont'd.)

	<u>Page No.</u>
Figure 11 - Cross Section Microstructures of 1/16-in. dia. Al Alloy Electrodes in the as Fabricated Condition	48
Figure 12a- Diagrammatic Representation of Potential Distribution Across a Direct Current Arc	49
Figure 12b- Illustrates Charge Carrier Flow of Direct Current Reverse Polarity (Electrode Positive) Welding Arc.	49
Figure 13 - Longitudinal Section Microstructures of 1/16-in. dia. 2319 Electrode in as Fabricated and Solution Heat Treated And Aged Conditions.	50
Figure 14 - Arc Stability for 1/16-in. dia. Modified 2319-Type Electrodes (Cu, Si, and Be).	51
Figure 15 - Cross section of Fractured 2-pass Weld Specimen in 1/2-in. 2219-T87 Plate With Filler B (3.5% Cu).	52
Figure 16 - Solution Potential Data for Gas Metal-Arc (MIG) Welds in 1/2-in. 2219-T87 Plate with Filler B (3.5 Cu) and 2319. . .	53
Figure 17a- Cross section of 1/16-in. 2319 Electrode Electroplated with Cu and Zn (5 min Zn plating), Filler H.	54
Figure 17b- Cross section of 1/16-in. 2319 Electrode Electroplated with Cu and Cd (5 min Cd plating), Filler I.	54
Figure 18 - Arc Stability for Zn and Cd Plated 2319 Compared with Bare 2319 and 5556 Electrode.	55
Figure 19 - Photograph of Weld Bead Deposited by Zn and Cd Coated 2319 Electrode.	56
Figure 20 - Arc Stability for 1/16-in. dia. Modified 2319-Type Electrodes (Zn, Cd, Mg).	57
Figure 21a- The Weld Region in 2219 Plate Welded with Filler K (2319 + 1.0 Zn). Specimen Cracked 1/2 in..	58
Figure 21b- The Grain Size of the Cracked Region in the Above Specimen at Higher Magnification .	58

TABLE OF CONTENTS (Cont'd.)

Page No.

Figure 22 - Shows the grain size of the cracked weld region in 2219 plate welded with 2319 filler. 3-1/2 in. of cracking occurred	59
Figure 23 - Shows the grain size of the cracked weld region in 2219 plate welded with filler P (.10 Ti, .01 V, .10 Zr) 13-1/4 in. of cracking occurred.	59
Figure 24 - Solution Potential Data for Gas Metal-Arc (MIG) Welds in 1/2-in. 2219 Plate with Filler K (1.0 Zn) and 2319	60
Figure 25 - Photograph of Weld Beads Deposited by 2319 and M789 (2319 + 1.0 Zn) Fillers in Flat Position	61
Figure 26 - Photograph of Weld Beads Deposited by 2319 and M789 (2319 + 1.0 Zn) Fillers in the Horizontal Position	62
Figure 27 - Arc Stability for 1/16-in. dia. 2319 and 2319 + Zn Electrodes (M788 and M789) with 100% Ar and 65% He-35% Ar Shielding Gases.	63

ARC STABILITY AND MELTING CHARACTERISTICS OF WELDING
WIRE FOR USE WITH 2319 ALUMINUM ALLOY PLATE

By

J. H. Dudas

ABSTRACT

21779

Two new experimental 2319-type electrodes, M788 (2319 + .25 Zn) and M789 (2319 + 1.0 Zn) were developed to provide a wider range of stable arc length and arc voltage than 2319 for gas metal-arc (MIG) welding 2219 plate. They permit a stable arc to be maintained with less precise control of weld conditions and a more favorable bead shape and size during out-of-position welding. Welds with these fillers were equal to or better than 2319 welds in tensile strength, freedom from cracking, and electrochemical potential in the weld zone.

Electroplating 2319 filler wire with zinc improved arc stability but interfered with current flow from the contact tube to the electrode. Plating was more costly than alloying.

Zinc was preferred to cadmium, magnesium, or calcium as a stabilizing addition because cadmium generated toxic fumes during welding, and magnesium and calcium significantly increased susceptibility to hot-short weld cracking.

2319-type electrode modified by lowering the copper content or adding silicon or beryllium did not have significantly improved arc stability. Strength and ductility of welds were decreased by these composition modifications.

Solution heat treating 2319 electrode reduced CuAl_2 particles in the wire microstructure but did not significantly improve arc stability.

Butler

INTRODUCTION

Aluminum is an attractive material for structural components of large space vehicles because strength-to-weight ratio is high and self-supporting structural rigidity is achieved. Among the high strength aluminum alloys 2219 (Al-Cu) provides the ease of welding and excellent cryogenic performance needed to meet the precise engineering demands of aerospace. Because of these outstanding features, 2219 alloy and its companion filler, 2319, have been selected for welded fuel tankage assemblies in the Saturn S-IC vehicle.

Experience at Marshall Space Flight center has shown that for gas metal-arc welding (MIG), 2319 electrode does not maintain a stable arc over as wide a range of welding conditions as electrodes of the 5000 Al-Mg series. As a result it is difficult to achieve desired bead configuration and uniform weld penetration, particularly for welds in the horizontal and vertical positions. Because of limited 2319 arc stability, the advantages of the MIG process have not been fully utilized for welding 2219 plate.

The object of this investigation was to examine arc stability and melting characteristics of 2319 electrode used for gas metal-arc welding 2219 plate and to improve arc characteristics by one of the following means: (1) heat treat the electrode, (2) coat the wire surface with a stabilizing element, or (3) modify the 2319 chemical composition.

MATERIALS AND EQUIPMENT

The filler metals included standard composition, 1/16-in. diameter electrodes 2319, 1100, 2014, 4043, 4145 and 5556, and electroplated 2319 and modified 2319-type compositions. The plate alloy was 1/2-in. 2219. Table I lists the compositions of these

alloys and the tensile properties of the electrodes.

Equipment for gas metal-arc welding consisted of:

1. Linde SVI 500 constant potential DC power supply (variable slope and inductance).
2. Aircomatic filler wire feeder, Model AHF-C, and Model AHF-B control.
3. Aircomatic pull gun Model AH-35A.
4. Airco No. 20 radiograph.
5. 36-in. welding table with grooved copper backup.

Welding current and voltage were recorded on Esterline Angus Model AW instruments. Shielding gases were Linde high purity dry (99.995 per cent) argon and Airco Grade A helium.

TEST PROCEDURES

A. Arc Characteristics

Arc stability and melting characteristics were evaluated while depositing weld beads on 1/2 x 6 x 24-in. 2219 plate. The plate surface was prepared by etching in 5 per cent caustic and 10 per cent nitric solutions. Welds were made either in the flat or horizontal positions with completely automatic procedures, using the following welding conditions, unless modified to study the effect of a particular variable:

1. 60 cu ft/hr argon shielding gas (5/8-in. diameter nozzle orifice).
2. 25 in./min travel speed.
3. 1/2-in. gas cup-to-work distance.
4. 5/8-in. contact tip-to-work distance.
5. 5° torch lead angle
6. Zero slope and inductor settings.

Welding current was varied within the range of 200-350 amps by adjusting the electrode feed rate. Arc voltage, controlled by turning a crank on the power unit, was measured between the

welding torch contact tube and ground connection terminal. Because no slope or inductance was added, the machine functioned as a nearly constant potential unit.

Arc characteristics were rated by visual observation and by studying the ampere-volt charts. An optical instrument was used for viewing the arc on a calibrated screen at a magnification of 2X. When mounted on the welding torch travel mechanism, it permitted metal transfer characteristics to be closely examined and visible arc length* to be measured within 1/16 in. and estimated to 1/32 inch. Figure 1 is a photograph of the welding setup.

B. Weld Cracking

Weld crack sensitivity for various filler alloys was determined with the Alcoa weld cracking test.¹ This test measures the amount of longitudinal cracking in the fillets of an inverted T-specimen having a 1/2 x 4 x 10-in. vertical member and a 1 x 4 x 10-in. base member. A photograph of a typical test specimen is shown in Figure 2. The specimen is manually welded by the gas tungsten arc process, employing a welding current of 300 amperes and an argon flow of 50 cu ft/hour.

Two variations of this cracking test may be employed--the "continuous bead" and the more severe discontinuous or "intermittent bead" test. The continuous test is employed to evaluate base metal/filler alloy combinations having a moderate or high susceptibility to cracking and the discontinuous test for combinations having a low tendency toward cracking.

C. Mechanical Tests

Tensile properties of welds in 1/2-in. 2219 plate were

*Arc length was defined as the observed distance between the electrode tip and the top of the work plate.

determined for selected fillers by standard weld tensile tests. Figure 3 illustrates the design for both full section (bead on) and reduced section (bead off) specimens. Welds were not tested that did not exhibit X-ray soundness at least as good as Class 2 ABMA-PD-R-27.

D. Corrosion Resistance

Weld corrosion performance was predicted by measuring the electrochemical potential of the various weld zones in 2219 plate. Solution potential surveys were conducted in a solution of 53 gm NaCl, 3 gm H₂O₂ per liter of distilled water. Selected areas were measured by masking the remainder of the specimens with wax before immersion. The reference electrode was 0.10 normal calomel.

PRELIMINARY RESULTS

A. Melting characteristics of Commercial Aluminum Electrodes

Initially various standard aluminum alloy electrodes were evaluated to compare alloy melting characteristics and arc stability. Included in the group were 2319 (Al-Cu), 1100 (Al), 4043 (Al-Si), 5556 (Al-Mg), 2014 (Al-Cu-Mg), and 4145 (Al-Si-Cu) alloys.

Melt-off rates for the various electrodes were compared by increasing the wire feed rate in several steps and noting the welding current at constant arc voltage. The results are shown in Figure 4. All alloys, except 5556, exhibited similar melt-off rates, as shown by the narrow band for 2319, 1100, 4043, 4145, and 2014 electrodes. 5556 electrode had a much faster melting rate for the same welding current. At 250 amps, for example, 5556 wire melted off at 295 in./min compared with approximately 225 in./min for other aluminum electrodes.

Magnesium electrodes have melt-off rates more than twice those of aluminum. When alloyed with aluminum, magnesium increases

the melt-off rate in proportion to the amount added. Al-Mg electrodes that contain smaller amounts of magnesium than 5556 (5052 and 5554 for example) have a melt-off rate between 5556 and Mg-free aluminum alloys.

Despite the different melt-off rate exhibited by 5556 electrode, the mode of metal transfer across the arc during welding was quite similar to other aluminum electrodes. As shown in Figure 5, all electrodes had similar melting characteristics at any given current, although the mode of metal transfer differed substantially at various current levels in the range of 200 to 350 amperes.

At 200 to 260 amps the molten metal was transferred across the arc as a mixture of large globular drops and finer droplet spray. This current range is approximately 75 amps above the transition current of 125-130 amps reported by several authors³⁻⁴ for 1/16-in. diameter aluminum electrodes. The transition current is the critical level of welding current where metal transfer suddenly changes from very large globular drops (larger than the electrode diameter) detached at a very slow rate to a mixture of smaller drops and fine spray transferred at a higher rate of frequency from the electrode. Welds can be deposited at a current just above the transition range, but it is not until approximately 200 amps are reached that sufficient melting rate and arc stability are achieved for normal welding. In the range of 200-260 amps the electrode assumes a blunt-nosed tip, and gravity, electromagnetic pinch effect and other forces within the arc cause the drops to be released from the electrode and accelerated toward the work piece at high speed. The arc is fairly stable with moderate force; the weld bead is narrow but generally uniform.

This range is desirable for flat position welds with low heat input and shallow penetration.

With increasing current, the molten drops become smaller and are transferred at greater frequency. At approximately 260 amps, the droplets become so small they are no longer visually detectable and the mode of metal transfer changes to a fine spray.

Spray transfer is characterized by a pointed electrode tip, a narrow axial arc column, and strong arc force. Weld penetration is deep and the bead contour is smooth and uniform. Axial-spray arcs are preferred for most welding applications because of deeper penetration and greater arc stability than globular-spray arcs. They are especially useful for out-of-position welding because the narrow arc column can be easily directed into horizontal or vertical fillets without affecting arc behavior.

Above 325 amps the arc force is so strong that the arc becomes quite erratic. The arc length varies without change in voltage or current, and beads are not uniform. With increasing current noticeable plunging of the arc occurs. The wire tip is alternately extended below the plate surface and burned back to expose the arc. The bead becomes very irregular--being composed of a series of blackened oxide folds. This is the very unstable condition termed "puckering" by British authors.⁵

The range of 260 to 325 amps provided best arc stability and deep weld penetration for all six aluminum electrode compositions. This range, however, is applicable only for 1/16-in. diameter aluminum electrodes. Other wire diameters experience the same general melting behavior, but the current ranges are higher for larger wire, lower for smaller wire.

B. Arc Stability - 5556 vs 2319 Electrodes

Arc stability was studied in detail for 5556 and 2319 electrodes in the axial-spray transfer range of 260 to 325 amperes. Figure 6 shows the relationship between current and arc voltage for these alloys at wire feed rates selected to provide similar currents. The current increased sharply with increased voltage for both electrodes until the arc stopped short-circuiting and became stable at $1/8$ - $5/32$ in. arc length. Little further current change was noted as the voltage was raised, although arc length increased appreciably. Between about 25 and 35 volts the welding current remained constant, while arc length increased to more than one inch.

The significant difference noted for the two electrodes was the magnitude of the stable arc range. 2319 electrode maintained a stable uniform arc for only a narrow range of voltage (23-25 volts) and arc length ($1/8$ - $1/4$ in.). Even within this range the arc was difficult to control because a small change in machine voltage settings caused an appreciable change in arc length. Above 25 volts ($1/4$ in. arc length) the 2319 arc began to flutter erratically and the electrode melted off less uniformly. The arc length alternately increased and decreased, and strong fluctuations in current and voltage were recorded. As the arc length was increased to $3/8$ in., the electrode tip bent slightly and began to rotate slowly about its major axis. The resulting weld bead was composed of uneven swirls having inconsistent contour and depth of penetration.

5556 electrode, on the other hand, maintained a stable arc over a wide range of voltage (22.5-27.5 volts) and arc length ($5/32$ - $3/8$ in.). Even at $3/8$ -in. length the arc was not noticeably unstable; however, this value was arbitrarily selected as the

upper limit where normal welding would be conducted. At longer arc lengths the bead became excessively wide, metal spatter increased, and penetration was not as deep.

Figure 7 illustrates the appearance of welds deposited for 2319 and 5556 electrodes. At short arc lengths both alloys exhibited uniform bead surface contour and almost no metal spatter along the edges. The last 1-1/2 in. of weld, which was not cleaned, shows that 5556 electrode generated more welding dust than 2319. A black deposit of finely divided aluminum particles can be seen along and adjacent to the 5556 weld. Only a small amount of this deposit surrounds the 2319 bead.

Welds deposited at 3/8-in. arc length are shown in the lower portion of the figure. The swirling, uneven bead deposited by 2319 contrasts with the uniform, smooth bead contour characteristic of 5556 electrode. Metal spatter was noticeably higher for 5556 but can be minimized in actual welding practice by changing the shielding gas composition or adjusting the characteristics of the power supply. These items will be discussed in other sections of this report.

C. Arc Stability - 1100, 2014, 4043, and 4145 Electrodes

Figure 8 compares the range of stable arc length and voltage for 1/16-in. standard electrode compositions at 270-290 amps welding current. Arc stability increases in this order: 2319, 1100, 4043, 4145, 2014, 5556. 1100 and 4043 electrodes produced unstable arcs somewhat similar to 2319 at arc lengths less than 3/8 inch. 1100 had a narrow stable range, like 2319, but its range of arc voltage was slightly wider (23.0-26.0) and more easily controlled with machine settings. The 4043 arc was more stable than that for 2319 or 1100. In addition, the weld deposit

did not exhibit the swirling bead configuration noted for 1100 and 2319 alloys. 2014 and 4145 exhibited a wide range of stable arc length similar to 5556 electrode, although closer control of voltage settings was required.

Weld beads deposited with the various electrodes at 3/8-in. arc length are illustrated in Figure 9. Arc stability and bead contour generally were better for alloys that generated greater amounts of welding dust and caused increased metal spatter at this long arc length.

Electrode composition thus is shown to be a principal factor in controlling arc stability for aluminum electrodes used for gas metal-arc welding (DCRP current). Commercially pure Al and Al-Cu alloys have inherently poor arc stability. Al-Si alloys exhibit improved arc characteristics, but large additions of Si appear necessary (10% in 4145) to achieve the desired level of stability. Magnesium, however, appears quite beneficial to arc stability even in relatively small quantities (0.5% in 2014).

D. Effect of Shielding Gas

Shielding gas composition has a profound effect on arc behavior during welding. For 5000 series Al-Mg alloys, an inert shielding gas containing 50-65 per cent He, balance Ar, was reported by Dowd⁶ to provide a more stable arc than pure Ar or other Ar-He mixtures. Weld spatter and porosity were reduced, permitting the use of wider ranges of arc voltage, current, and travel speed.

Bead-on-plate tests comparing arc stability for 100 per cent Ar versus a 65 per cent He-35 per cent Ar shielding gas were conducted for 1/16-in. 2319 and 5556 electrodes. The results are shown in in Figure 10. The benefit of Ar-He for welding Al-Mg alloys was confirmed. The 65 He-35 Ar mixture permitted arcs with

5556 electrode to stabilize at a shorter length and over a wider range of arc length and arc voltage than pure argon. Although a higher arc voltage was required to achieve the same arc length as in pure Ar, weld spatter was noticeably reduced.

With 2319 filler, Ar-He mixtures also required a higher arc voltage, but arc stability was not improved. 2319 exhibited an even narrower range of stable arc length and voltage than with pure Ar, requiring very precise weld machine settings to maintain a stable arc. Because of the erratic behavior of 2319 with Ar-He mixtures, further comparison weld tests with experimental electrodes were made using only 100 per cent Ar shielding.

E. Electrode Microstructure

One reason advanced for the inherently poor arc stability obtained for 2319 is its microstructural difference from other electrodes. Metallographic studies of 2319 electrode have revealed, in many instances, the presence of undissolved particles (mostly CuAl_2) throughout the microstructure. It was thought that these particles, if large enough, could conceivably interfere with metal transfer characteristics during welding and reduce arc stability.

CuAl_2 particles are present in 2319 because of a high copper content (6.3% nominal). During ingot solidification aluminum-rich dendrites freeze first, pushing the copper aside to enrich the remaining liquid. The last liquid to freeze contains copper at about the eutectic composition. Despite preheating to homogenize the structure, CuAl_2 is present throughout the cast ingot. During fabrication into wire, constituents are broken into particles visible only under the microscope. Figure 11 illustrates a typical 2319 wire cross section microstructure along

with comparative structures for 5556, 4043, 4145, and 2014 electrodes. CuAl_2 may be seen in both 2219 and 2014 microstructures. For 2014 electrode, however, the particles are smaller and more widely distributed. Microstructures of 4043 and 4145 show small silicon particles. Very little undissolved constituent is in the 5556 microstructure because of the high solid solubility of magnesium in aluminum.

DISCUSSION OF PRELIMINARY RESULTS

In order to discuss the metallurgical factors affecting arc stability and melting characteristics of aluminum electrodes, it is necessary to consider the nature of the electric arc during welding. As shown in Figure 12a, the electric arc consists of three main regions of differing potential gradients--the arc column, the anode, and the cathode regions.⁷ The arc column constitutes the largest portion of the arc and has a small, uniform potential gradient along its length. The steepest potential drops occur at the anode and cathode. When the arc length is increased the arc column expands, but little change occurs in the anode and cathode regions. An accurate balance of negative electrons and positive ions is needed to maintain a stable arc column.

For gas metal-arc welding (electrode positive) the work plate is the cathode and the consumable electrode the anode (Figure 12b). A large cathodic area is available to maintain the supply of electrons, but the positive charges must come from either or both of two sources: (1) ionized gas atoms from the inert gas stream, or (2) ionized metal vapors from the melted electrode. Welding arcs that develop fine metal spray provide more metal vapor than globular spray arcs and thus exhibit better arc stability.

Table II lists the ionization potential, boiling point, and thermionic work function for selected chemical elements. The metals are generally more easily ionized than argon or helium gases used for shielding. If vapors from these metals are present in substantial quantities, they provide an abundant source of ions for stabilizing the welding arc.⁷

Although aluminum and copper are easily ionized, they vaporize at a relatively high temperature. As a result few ionized metal vapors are provided during gas metal arc welding with 1100 (Al) or 2319 (Al-Cu) electrodes. The arc column must therefore rely on the shielding gas to supply positive ions. At arc lengths above 1/4 in., however, even this source apparently does not provide sufficient ions and the arc becomes unstable. Helium is more difficult to ionize than Ar and explains why Ar-He mixtures produce a less stable arc than pure argon during welding with 2319.

Magnesium has the desirable characteristics of: (1) a low ionization potential, and (2) a low vaporization temperature. When present as an alloying element in aluminum electrodes (5556 and 2014, for example), magnesium provides an abundant source of easily ionized metal vapors that stabilize the welding arc. This is borne out by weld bead photographs, which show the smoothest beads and largest amounts of welding dust were exhibited by Mg-containing electrodes.

Inasmuch as magnesium improves arc stability, other easily ionized elements that vaporize at about the same temperature as magnesium should also be beneficial for welding. Zinc, cadmium, and calcium are elements of this type and should help stabilize the welding arc when present with Al or Al-Cu electrodes either as alloying constituents in the wire or as coatings on the electrode.

Silicon also appeared to aid arc stability, but quantities on the order of 10 per cent by weight were needed in an Al-4 Cu alloy to achieve the stable arc characteristics provided by 0.5 magnesium. Silicon vapors are relatively easily ionized, but like copper a high temperature is needed for vaporization. Silicon would not be expected to improve arc stability in the same manner as magnesium. When alloyed with aluminum, however, silicon has been shown to reduce surface tension of the liquid metal.⁸ At the 10 per cent silicon level droplet formation and metal transfer may be improved by the reduced surface tension--resulting in a more stable welding arc. If this mechanism is true, then beryllium, which in very small quantities reduces surface tension of many molten aluminum alloys, may also be beneficial. Beryllium, however, is extremely toxic in the vaporized form and must be held to very small concentrations ($<0.0008\%$) in welding electrode.

One notable factor affecting arc characteristics that has not been considered is thermionic work function. The lower the work function of the cathode, the more easily electrons are emitted for sustaining the welding arc.⁹ Refractory materials like tungsten make excellent electrodes because they have both an inherently low work function and a high boiling temperature. Tungsten emits sufficient electrons below its boiling temperature to easily sustain a straight polarity (electrode negative) arc.

Most structural metals have a lower work function than tungsten, but because of their lower boiling temperature, fewer electrons are emitted for welding. If the cathode area is small, as in gas metal arc welding (electrode negative), insufficient electrons are produced to maintain a stable arc. This is why gas metal arc welding of aluminum enjoys success only with reverse

polarity current (electrode positive). The cathode area is large and ample electrons are available to maintain a stable welding arc. Unstable arcs appear to be caused by a shortage of positive ions to balance the supply of electrons rather than insufficient electrons. For gas metal arc welding (electrode positive) then, the ionization potential and boiling temperature of the electrode are of more significance to arc stability than thermionic work function.

PROPOSED PROGRAM

Based on the foregoing preliminary results and discussions, the following program was established to improve arc stability of 2319 (Al-Cu) electrode during gas metal-arc (MIG) welding of 2219 plate:

1. Solution heat treat 2319 electrode to reduce particle constituents within the microstructure that may interfere with metal transfer characteristics.
2. Alloying 2319 with elements that reduce the surface tension of molten aluminum such as Si or Be.
3. Alloying 2319 with elements that have both a low vaporization temperature and a low ionization potential such as Mg, Zn, Cd, and Ca.
4. Electroplating 2319 electrode with elements having these same characteristics. Zn and Cd are most easily electroplated on aluminum.

PROGRAM RESULTS

A. Heat Treated 2319 Electrode

An attempt was made to improve 2319 arc stability by subjecting the wire to a conventional solution heat treatment of 1/2 hr at 1000°F. A large portion of the copper is dissolved at this temperature and should reduce any large CuAl_2 particles in the wire microstructure.

The initial attempt to solution heat treat small diameter

1/16-in. wire in a normally dry atmosphere resulted in reducing the amount and size of CuAl_2 particles but caused hydrogen to be absorbed by the wire. Hydrogen could be detected in the wire microstructure, which during welding, ignited in erratic bursts and interfered with arc stability studies.

A quantity of low hydrogen (.07 cc/100 gm) 2319 electrode was produced by employing an extremely dry atmosphere (-27°F dew point) and a longer (8 hrs) solution heat treatment. The wire was quenched after heating and naturally aged. Figure 13 compares the microstructure of the solution heated and aged wire with that in the as-fabricated condition. The amount and size of CuAl_2 particles (white constituents) are seen to be reduced by the thermal treatment. Arc stability tests, however, showed the range of stable arc length and voltage for the heat treated wire was not significantly better than the as-fabricated electrode.

Solution heat treatment, therefore, offers no apparent advantage for 2319 electrode. Arc characteristics are not improved, and such treatment would be difficult to conduct commercially because small diameter wire has such a large surface area to volume ratio that susceptibility to hydrogen absorption is high.

B. Modified 2319 Type Alloys - Cu, Si, and Be

2319-type alloys having either reduced copper or added silicon or beryllium were examined for arc stability as well as weld strength and corrosion resistance. Six alloys with modified copper or silicon were available from another investigation. One alloy containing beryllium was cast and fabricated specifically for this work. The compositions of all seven alloys are listed in Table I as filler A through G.

1. Arc Stability and Melting Characteristics

Three of these fillers, B(3.5 Cu), C(5.2 Cu-1.2 Si), and G(2319 + .0004 Be) were selected for detailed arc studies.

Metal transfer characteristics were found to be similar to other aluminum alloys as previously shown in Figure 5--with axial-spray transfer commencing around 260 amperes. Results of arc stability tests within the spray transfer range are shown in Figure 14. All three of the experimental electrodes exhibited slightly better arc stability than 2319, but none approached the desirable characteristics noted for 4145 or 5556 electrodes. Filler C(5.2 Cu-1.2 Si) had slightly better arc characteristics than the other fillers and tended to more easily "wet" the 2219 plate. Larger additions of silicon would be expected to further improve arc stability--but only at some sacrifice in weld properties.

2. Weld Mechanical Properties

Welds were made in 1/2-in. 2219-T87 plate with all electrodes using a 60° double Vee joint configuration to assure the weld would contain a high percentage of melted filler metal. Welds with filler G(2319 + Be) were not mechanically tested because radiographic inspection revealed severe porosity of Class III to V rating. Other fillers had Class I or II weld soundness. Table III lists the weld conditions and compares as-welded tensile properties for welds with various fillers.

Highest weld strengths were achieved with experimental fillers that did not contain silicon; however, these alloys had lower copper content than 2319 and strengths were 3 to 4 KSI below those for 2319. Increasing amounts of silicon tended to lower both weld strength and ductility. Lowest weld properties were obtained for filler F, which had the lowest copper (2.4%)

and highest silicon (4.0%). Figure 15 illustrates the cross section of a full section weld (bead on) deposited with Filler B (3.5% Cu). This weld failed at 39,000 psi and in a fracture pattern typical of most welds performed in this work.

3. Predicted Corrosion Behavior

The predicted corrosion performance of welds in 2219-T87 plate with the various experimental fillers was determined by solution potential measurements in the weld zones. The solution potential survey provides a rapid means of predicting weld corrosion behavior.¹⁰ Areas of high negative potential (anodes) preferentially corrode to protect the more electropositive zones (cathodes). No selective attack occurs when the weld, heat affected zone, and unaffected parent metal are all of the same solution potential. Second best is when the weld bead is cathodic to the heat affected zone and parent plate. The base metal then acts as a large anode that corrodes at a very slow rate and protects the smaller weld zone. The worst possible condition is when the weld bead or heat affected zone is anodic to the parent plate. These narrow areas will corrode rapidly to protect the large cathodic base metal. The rate of selective attack increases with: (1) increase in potential difference between the anode and cathode, and (2) decrease in anode area.

The solution potential of Al-Cu alloys is determined by the amount of copper solid solution with aluminum. The greater the amount of copper in solution the more cathodic the alloy. During solution heat treatment of an Al-4 per cent Cu alloy, for example, nearly all the copper goes into solution and decreases the anodic potential from -840 to -690 millivolts. Artificial aging at temperatures in the vicinity of 375°F precipitate copper

from the Al-Cu solid solution and increase the electrode potential. Silicon has relatively little effect on the electrode potential of aluminum when in solid solution, because of its relatively low solid solubility.

In order to evaluate corrosion performance of these electrodes in welded plates, solution potential measurements were conducted in the weld area, heat affected zone, and unaffected 2219 base metal. Unmasked strips approximately 1/8-in. wide and parallel to the weld were exposed to a solution of NaCl-H₂O₂. Solution potential data for welds in 2219-T87 plate with 2319 alloy and a 3.5 per cent copper filler are plotted in Figure 16. The weld beads did not have substantially different anodic potential values despite the difference in copper level of the fillers. This can probably be attributed to partial dilution of the 3.5 Cu weld with melted 2219 base metal (6.3 Cu), causing an increase in weld copper content. The amount of copper remaining in solid solution after cooling then may have been nearly the same for both weldments (approximately 4 per cent according to solution potential values).

Welds with other experimental fillers having reduced copper and higher silicon had solution potential values similar to the listed alloys. In all cases the weld and heat affected zones were protected by the more anodic 2219-T87 plate. Selective attack would not normally occur under these conditions, and all fillers should exhibit good corrosion performance in the as-welded condition. Heat treatment after welding would, of course, change the weld and plate electrode potentials and could cause a lower copper weld bead to become anodic to the base metal. Further study would be required to predict corrosion behavior of heat treated weldments.

C. Electroplated 2319 Electrode - Zn and Cd

Fifty-foot lengths of 1/16-in. diameter 2319 were chemically cleaned, flash copper coated, and electroplated with zinc or cadmium for periods of 2, 5, and 10 minutes. The plated wires were designated fillers H (Zn coated) and I (Cd coated). Table IV lists the average coating thicknesses as determined metallographically, and Figure 17a and b shows various coating thicknesses in a cross section of wire plated for five minutes.

1. Arc Stability and Melting Characteristics

Arc stability tests were conducted at 260-300 amps current, which was within the region of best arc stability and bead appearance for 2319 electrode. Fillers with zinc or cadmium coatings exhibited considerably better arc stability than uncoated 2319. This is illustrated in Figure 18. Fillers H and I (0.00005 in. avg coating thickness) became stabilized at a lower arc voltage and over a wider range of arc length and arc voltage than 2319 and approached the stability of 5556 electrode. Electrodes with thicker plated coatings (Table IV) exhibited no further improvement in arc stability but became stabilized at a slightly lower arc voltage. These electrodes also generated greater quantities of welding dust and metal spatter. Vapors and dust from the Cd plated electrode were characteristically yellowish in color and contained toxic cadmium oxide. Strict attention to proper ventilation was required during welding with this filler.

Other characteristics noted for the plated electrodes were:

- a. The arc assumed a characteristic multiple color pattern that differed for each electrode. The zinc plated filler exhibited a white arc column enveloped by narrow but distinctive zones of green and orange extending to the outer periphery of the arc. Just below the electrode tip at the peak of the arc column was a C-shaped zone of purple. The arc produced by the cadmium plated wire had a green bell-shaped center extending the length of the arc column and was surrounded by a zone of bright red. These color patterns were of no significance to this work but may be indicative of temperature zones within the arc.
- b. Metal transfer characteristics differed markedly from that for bare 2319. The region of axial-spray transfer that commenced around 260 amps for other aluminum electrodes did not begin until approximately 300 amps for the plated fillers. Below this, current metal transfer was of the globular-spray type.
- c. Arc length varied about $+1/16$ in as the weld progressed along the plate. This appeared to be caused by variations in surface resistance of the electrode due to variations in coating thickness.

The last item was studied in more detail by measuring the resistance to current flow across the plated surface. Table V shows that the mean surface resistance of zinc coated 2319 was nearly $2-1/2$ times that for uncoated electrode and varied more from point to point along the electrode surface. As a check on surface resistance data, the voltage drop between the contact tube and the electrode was measured during welding. Considerable voltage fluctuation was detected. Approximate average values, shown in Table VI, for the plated electrodes were again 2 to $2-1/2$ times greater than the unplated wire--confirming that a high surface resistance was present. Basic arc stability was not affected by the observed variations in arc length but weld bead shape was somewhat irregular when welding at short arc lengths. This is shown in Figure 19. Of the two plated elements, zinc appeared to affect bead configuration more than cadmium and exhibited slightly more metal spatter.

Zinc and cadmium platings definitely provide the improved arc stability needed for 2319 electrode; however, the high cost of electroplating as compared to alloying and the expected difficulties in obtaining a uniform coated thickness ruled out this approach until alloying techniques had been fully investigated.

D. Modified 2319 Type Alloys - Zn, Cd, Mg, Ca, Zr, and V

The six modified 2319 compositions, listed in Table I as Fillers J (0.27 Zn), K (1.0 Zn), L (0.23 Cd), M (0.12 Mg), N (0.53 Mg), and O (0.20 Ca) were cast and fabricated into experimental quantities of 1/16-in. diameter electrode. Tests were conducted to determine which element provided the most improved arc stability and melting characteristics in 2319 with the least adverse effect on weld cracking, mechanical properties, or corrosion resistance. Two additional 2319 type compositions with reduced grain refining elements vanadium or zirconium, Fillers P (0.0 V) and Q (0.0 V and Zr), were prepared for inclusion in the weld cracking test portion of the program.

1. Arc Stability and Melting Characteristics

The results of the arc stability tests are plotted in Figure 20. 2319 type alloys with zinc (Fillers J and K) and cadmium (Filler L) exhibited markedly better arc stability than 2319--being equal to 5556 filler in range of stable arc length and arc voltage.

Both the zinc and cadmium containing electrodes exhibited a much smoother bead surface than 2319 at longer arc length but generated more welding dust and metal spatter. Filler K (1.0 Zn) was worse than others in this respect but had less spatter than previously noted for 5556. All three electrodes, however, demonstrated the improved arc stability needed for easily controlled

gas metal arc welding of 2219 plate.

Filler M (0.12 Mg) had a higher degree of arc stability than 2319 but did not contain sufficient magnesium to approach the excellent characteristics of the other fillers. Filler N, which had a larger magnesium addition (0.5%) and Filler O (0.2 Ca) were not evaluated for arc stability because of high susceptibility to hot short weld cracking.

2. Weld Cracking

Weld cracking for 2219 base metal welded with experimental 2319-type fillers is compared with 2319 electrode in Table VI. Fillers with zinc or cadmium (Fillers, J, K, and L) cracked an average of only 1/2 in. on the severe discontinuous test. These fillers were even slightly less crack sensitive than 2319 and would provide excellent resistance to weld cracking in all joint configurations.

Fillers N (0.53 Mg) and O (.20 Ca) cracked 16-3/4 and 11 in. respectively in this test. Cracking may occur during normal welding with these fillers if joint restraint is high. Both magnesium and cadmium in these amounts tend to alter the freezing characteristics of Al-Cu alloys, causing higher hot shortness during weld solidification. Filler M (0.12 Mg) had lower magnesium content and cracked about the same level as 2319; however, it did not exhibit good arc stability. In view of the unpromising results for fillers with additions of magnesium and calcium, further experimental weld tests were limited to alloys with zinc or cadmium.

Table VI also lists weld cracking results for two other fillers, P and Q, which were prepared with vanadium and zirconium purposely held below the normal level for 2319 to determine if these elements were essential to achieve low weld cracking. Welds

with these fillers developed substantially higher cracking than welds with 2319 or 2319 + Zn fillers. Close control of weld conditions would be required to achieve crack-free welds, particularly in repair welding or difficult joint configurations.

Figures 21 to 23 show the influence of weld grain size on weld crack sensitivity. Figure 21a is a cross section of the weld region in 2219 plate welded with Filler K (1.0 Zn), which cracked only 1/2 inch. As shown in Figure 21b, the specimen had a very fine weld grain size. Figures 22 and 23 compare the grain size of welds performed with 2319 and Filler P (.01 V). With Filler P, welds had a much coarser grain size and cracked 13-1/4 in. versus only 3-1/2 in. for 2319. Zirconium and vanadium are needed in 2319 to maintain good resistance to weld cracking.

3. Weld Mechanical Properties

Weld mechanical properties were determined for fillers with zinc and cadmium additions because these electrodes displayed both improved arc stability and had good resistance to weld cracking. Table VI lists the tensile properties and procedures for welded 1/2-in. 2219-T87 plate tested in the "as welded" condition. Welds for all electrodes except filler J (0.27 Zn) approached the standard properties previously noted for 2319 filler. Filler J developed approximately 2000 psi lower strength than 2319 and had the most variations in results obtained for four tests. These marginal differences, however, did not appear to be caused by differences in electrode chemistry. Neither zinc or cadmium, in amounts shown, notably influenced the mechanical properties of welds in 2219 plate.

4. Predicted Corrosion Behavior

Figure 24 compares the solution potential results for Filler K (1.0 Zn) and 2319 weldments in the: (1) as-welded, (2) welded and aged, and (3) welded, solution heat treated, cold water quenched, and aged conditions. Welds with Filler K had only a slightly higher potential than those with 2319 electrode. In the as-welded or welded and aged conditions, both Filler K and 2319 weld beads were cathodically protected by the heat affected zone and base metal. Little selective attack would normally occur under these circumstances. Welds that were solution heat treated and aged, however, exhibited the most desirable conditions because the weld, heat affected zone, and base metal were all at about the same solution potential.

Solution potentials for welds with Filler J (.27 Zn) and Filler L (.23 Cd) were between those of Filler K and 2319. Welds with all experimental fillers should exhibit the same good corrosion performance as now obtained with 2319 electrode. Actual corrosion performance must be determined, however, by exposing welded panels to appropriate corrosion environments.

5. Metal Fume Toxicity

Cadmium can become quite toxic if heated high enough to allow the formation of cadmium oxide fumes. Severe respiratory ailment, and even death, may result if concentrations in excess of the allowable threshold limit of .1 mg CdO/m³ are breathed for prolonged periods of time. Because of this danger, Alcoa's Industrial Hygiene group was asked to sample the dust and fumes generated near the operator's breathing zone during gas metal arc welding with Filler L (2319 + .23 Cd). Two samples were collected at 280 amps current with no room or local exhaust ventilation in order to represent the worst possible welding conditions encountered.

These samples had cadmium oxide concentrations of 4.4 and 6.9 mg/m³, respectively. These values were 44 to 69 times the allowable threshold limit of 0.1 mg CdO/m³, indicating that rigid ventilation procedures need to be observed for safe welding with this electrode. Because of this hazard, and the fact that zinc additions were as effective as cadmium for arc stability, it was decided to discontinue any further testing with the cadmium-containing filler.

Zinc is not a toxic metal, but noxious metal fume fever can result if zinc or magnesium fumes are inhaled in amounts exceeding the threshold limit of 15.0 mg/m³. Chills, fever, and nausea usually occur within four to eight hours after exposure and disappear almost invariably within 24 hours. Normal exhaust procedures, as recommended in reference 11, should provide adequate protection for electrodes with zinc or magnesium.

E. Characteristics of 2319 + Zinc Electrodes

Zinc, when alloyed with 2319 in amounts of 0.25-1.0 per cent, provides an improved electrode for gas metal-arc welding of 2219 plate. Arc stability is notably improved over that for conventional 2319 because easily volatilized zinc vapors are readily ionized to provide an abundance of positive ions for maintaining the reverse polarity arc. Susceptibility to hot short cracking, weld tensile properties, and predicted corrosion behavior are not adversely affected by the added zinc. Because of these outstanding features, electrodes J (.27 zn) and K (1.0 Zn) were redesignated as experimental alloys M788 and M789, respectively, and selected for further comparison tests with 2319 filler. Five pound quantities of 1/16-in. diameter M788 and M789 were sent to Mr. D. Daley, Marshall Space Flight Center for his evaluation.

1. Horizontal Position Welds

In order to determine if M788 and M789 electrodes exhibited notably better arc stability than 2319 for "out of position" welding, bead on plate tests were conducted in the horizontal weld position. All electrodes exhibited the same range of arc stability in the horizontal position as in the flat position; however, bead shape and size were somewhat more difficult to control. As a result, weld settings for 2319 filler had to be very precisely "tuned in" because of its inherently narrow range of stable arc length and arc voltage. At 1/4-in. arc length and above, weld bead shape and contour for 2319 were undesirable for normal welding. The zinc containing electrodes, however, exhibited little change in bead characteristics within the wide range of 1/8 to 3/8-in. arc length. This can be seen in the weld bead photographs illustrated in Figures 25 and 26.

2. Shielding Gas Composition

A few tests were run comparing argon and helium-argon shielding gas mixtures for welding M788 and M789. These results are shown in Figure 27, along with comparative data for 2319. Unlike 2319, the range of stable arc length and arc voltage for zinc containing electrodes was virtually the same for both pure argon and a 65 helium-35 argon mixture. As noted previously, however, a voltage increase of 2-1/2 to 3 volts was required to achieve the same arc length as with pure argon gas. This resulted in a wider bead but with noticeably less spatter. The helium-argon mixture also reduced welding current 15 to 20 amperes for the same wire feed rate as pure argon, thus permitting higher melting rates to be achieved. If the higher voltage requirements are not a detriment to "out of position" welding, then a 65 helium-

35 argon mixture may prove the best shielding gas composition for M788 and M789 electrodes.

3. Power Supply Characteristics

No slope or inductance were added to the constant potential source machine used in this investigation in order to permit a more valid comparison to be made among the changing electrode compositions. Normally, however, some adjustments in power characteristics are desirable to minimize the effect of current variation on arc length, to reduce weld spatter, and to improve puddle fluidity. For the more finalized zinc containing compositions, added slope and inductance appear desirable to achieve optimum arc characteristics. Actual values, however, will need to be determined for each specific welding job.

CONCLUSIONS

1. 2319 welding electrode alloy exhibited a narrower range of arc stability than aluminum alloy electrodes 5556, 2014, 4043, and 4145 for gas metal-arc (MIG) welding 2219 alloy plate.
2. Additions of volatile, easily ionized elements such as zinc, cadmium, or magnesium to 2319 provided excellent arc stability similar to the aluminum-magnesium alloy 5556. Zinc was preferred to cadmium, magnesium, or calcium as a stabilizing addition because cadmium generated toxic fumes during welding and magnesium and calcium significantly increased weld cracking.
3. M788 (2319 + .25 Zn) and M789 (23.9 + 1.0 Zn) electrodes combined desirable arc stability for gas metal-arc welding 2219 plate with low sensitivity to cracking, high weld strength, and favorable weld zone electrochemical potentials.
4. Electroplated zinc and cadmium on 2319 wire markedly improved arc stability but interfered with current flow from the contact tube to the electrode.
5. Additions of silicon (1.2%) or beryllium (.0004%) to 2319 type electrodes to reduce surface tension of molten aluminum did not substantially improve arc stability. Strength and ductility of welds in 2219 plate were decreased by silicon additions to the electrode.

6. Solution heat treating 2319 electrode reduced CuAl_2 particles in the wire microstructures but did not significantly improve arc stability.
7. A 65% He-35% Ar shielding gas mixture increased M788 and M789 melt-off rates and reduced weld spatter with no apparent decrease in arc stability.
8. Eliminating zirconium or vanadium to reduce segregation in 2319 type electrode dangerously increased susceptibility to weld cracking.

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that future work be directed toward establishing the most desirable zinc level in 2319 to achieve good arc stability, weld mechanical properties, and corrosion performance. This may be accomplished with the following specific programs:

1. Cast one additional 2319-type composition containing 0.5 per cent zinc and compare arc stability with electrodes containing 0.25 and 1.0 per cent zinc. Determine optimum zinc level needed for good arc stability and bead shape with minimum weld spatter.
2. Evaluate mechanical properties of welds made with 2319 + zinc fillers in several plate thicknesses at both normal and cryogenic temperatures. Sufficient work needs to be done to determine if weld properties with these fillers differ from 2319 welds given the following thermal treatments: (a) -T87 plate (as welded), (b) -T37 plate post weld aged to -T87, and (c) -O or -F plate reheat treated and aged to -T62.
3. Evaluate general and stress corrosion performance of welds with the zinc containing fillers in several 2219 plate thicknesses employing the thermal treatments described above. Sufficient work needs to be accomplished to determine if corrosion resistance differs from 2319 welds exposed to various corrosive environments.
4. Evaluate feasibility for commercially fabricating various electrode diameters of 2319 with final selected zinc level.

REFERENCES

1. J.D. Dowd, Welding Journal 31, Oct. 1952
2. L.F. Lockwood, Welding Journal 42, Oct. 1963
3. A. Lesnewich, Welding Journal 37, Sept. 1958
4. J.C. Needhorn, C.J. Cooksey, D.R. Milner; British Welding Journal 7, No. 2, Feb. 1960

5. J.C. Needhorn, A.A. Smith; British Welding Journal 5, Feb. 1958
6. J.D. Dowd, Welding Journal 35, Apr. 1956
7. D.R. Molner, G.R. Salter, J.B. Wilkenson; British Welding Journal 7, Feb. 1960
8. M.A. Miller, Welding Journal 35, Feb 1946
9. A. Lesenwich, Welding Journal 37, Aug. 1958
10. F.R. Collins, Welding Journal 41, Aug. 1962
11. American Standards Booklet Z-49.1-1958

TABLE I

COMPOSITIONS AND TENSILE PROPERTIES OF 1/16-IN DIAMETER ALUMINUM ALLOY ELECTRODES

Filler Alloy	Lot No	Composition													Electrode Tensile Data*			
		Cu	Mg	Fe	Si	Mn	Zn	Ni	Cr	Ti	V	Zr	Cd	Be	Ca	TS	YS	% El (10")
2319	098081	6.24	.01	.20	.11	.24	.11	.01	.00	.11	.08	.13	-	-	-	40,770	32,800	1.2
5556	000451	.02	5.17	.19	.09	.77	.01	.00	.09	.09	-	-	-	-	-	50,830	25,700	16.1
2014	624544	4.40	.38	.39	.86	.78	.10	.01	.01	.04	-	-	-	-	-	27,400	16,200	10.0
4043	467211	.00	.00	.27	5.44	.00	.00	.00	.01	.00	-	-	-	-	-	27,270	21,400	1.5
4145	21482051																	
	4.17	.02	.36	10.0	.02	.00	.00	.01	.01	.01	-	-	-	-	-	36,430	30,700	1.8
A	204094	5.33	.00	.14	.11	.28	.04	.02	.00	.13	.11	.14	-	-	-	27,970	16,600	11.0
B	204095	3.45	.00	.14	.10	.26	.04	.01	.00	.11	.08	.13	-	-	-	26,200	18,000	10.0
C	204098	5.17	.00	.16	1.16	.26	.04	.02	.00	.12	.09	.14	-	-	-	26,900	17,500	10.9
D	204043	4.45	.00	.13	.12	.29	.01	.00	.00	.12	.09	.16	-	-	-	24,530	11,100	13.9
E	204096	4.47	.00	.15	1.98	.30	.03	.02	.00	.14	.09	.14	-	-	-	28,500	17,200	11.0
F	204097	2.43	.00	.18	3.95	.30	.03	.02	.00	.14	.10	.14	-	-	-	26,830	19,500	8.8
G	226039	6.30	.00	.18	.11	.28	.02	.00	.00	.13	.09	.11	.00	.0004	-	28,300	20,550	8.4
H**	285312	Zinc coated 2319 (Lot 098081)																
I**	285313	Cadmium coated 2319 (lot 098081)																
J(M788)	226036	6.36	.00	.18	.11	.29	.27	.01	.00	.13	.10	.11	.00	.0000	-	26,740	16,300	11.0
K(M789)	226037	6.40	.00	.18	.11	.29	1.00	.01	.00	.13	.10	.11	.01	.0000	-	26,440	17,800	9.9
L	226038	6.32	.00	.18	.11	.30	.02	.01	.00	.14	.10	.11	.23	.0000	-	27,420	20,800	9.0
																		31

TABLE I (Contd.)

Filler Alloy	Lot No	Composition													Electrode Tensile Data*			
		Cu	Mg	Fe	Si	Mn	Zn	Ni	Cr	Ti	V	Zr	Cd	Be	Ca	TS	YS	% El (10")
M	285399	6.16	.12	.19	.09	.29	.00	.00	.00	.13	.09	.16	-	-	.00	-	-	-
N	285400	6.16	.53	.18	.09	.29	.00	.00	.00	.14	.09	.15	-	-	.00	-	-	-
O	285401	6.15	.00	.19	.08	.29	.00	.00	.00	.13	.10	.15	-	-	.20	-	-	-
P	285402	6.24	.00	.19	.08	.29	.00	.00	.00	.10	.01	.10	-	-	.00	-	-	-
Q	285403	6.46	.00	.24	.08	.29	.00	.00	.00	.09	.00	.00	-	-	.00	-	-	-
1100	039881	0.13	.00	.50	0.09	.01	.00	.00	.00	.00	-	-	-	-	-	-	-	-
Base Metal																		
2219		6.23	.00	.23	.10	.27	.01	.00	.00	.06	.09	.16	-	-	-	-	-	-

*Experimental electrodes were annealed to facilitate chemical cleaning and spooling.

**Cleaned in caustic soda and nitric acid, zincate treated, flashed with copper plating, electroplated with zinc or cadmium.

TABLE II
SELECTED PHYSICAL PROPERTIES THAT INFLUENCE
WELDING CHARACTERISTICS

<u>Element</u>	<u>Ionization Potential (e.v.)</u>	<u>Boiling Point (°F)</u>	<u>Thermionic Work Function (e.v.)</u>
Aluminum	5.96	4440	4.00
Copper	7.68	4700	4.50
Magnesium	7.61	2030	3.70
Cadmium	8.96	2625	4.00
Zinc	9.36	1663	3.60
Calcium	6.09	1440	2.70
Silicon	8.12	4200	4.50
Beryllium	9.28	5020	3.90
Tungsten	8.1	10,700	4.52
Argon	15.68	-302	-
Helium	24.46	-452	-

TABLE III

PROPERTIES OF MIG WELDS IN 1/2-IN. 2219-T87 PLATE WITH
1/16-IN. DIAMETER EXPERIMENTAL 2319 TYPE ELECTRODES

Filler Alloy	Welding Conditions* Volts Amps		Tensile Test Data**			
			Bead On		Bead Off	
			(psi)	% El 2 in.	10 in.	TS (psi)
2319 (6.2 Cu)	23.0	275	42,180	5.2	1.1	40,580
A (5.3 Cu)	23.0	280	38,100	4.9	1.0	38,100
B*** (3.5 Cu)	23.0	275	38,950	5.0	1.0	37,800
C*** (5.2 Cu- 1.2 Si)	22.0	280	37,080	4.6	1.0	33,920
D (4.5 Cu)	22.5	280	38,200	5.5	1.2	37,520
E (4.5 Cu- 2 Si)	23.0	270	36,370	4.8	1.0	37,870
F (2.4 Cu- 4.0 Si)	22.0	280	35,120	4.0	0.8	35,050

*Welded in flat position, one pass from each side, employing 60° double V joint with 1/16-in. land, 16 to 20 ipm travel speed. X-ray examination revealed Class I or II soundness.

**Average of four tests varied within ±1000 psi except fillers C and F, which varied within ±1500 psi. All failures occurred in weld metal.

***Electrodes sent to Marshall Space Flight Center for evaluation.

TABLE IV

COATING THICKNESSES FOR 1/16-IN. DIAMETER 2319 ELECTRODE
ELECTROPLATED WITH ZINC AND CADMIUM

Filler Alloy	Plating Time	Avg Cu Thickness	Avg Zn Thickness	Avg Cd Thickness
H	2 min	0.0001 in.	0.00005 in.	-
	5 min	0.0001 in.	0.0001 in.	-
	10 min	0.0002 in.	0.0002 in.	-
I	2 min	0.0001 in.	-	0.00005 in.
	5 min	0.0004 in.	-	0.0001 in.
	10 min	0.0004 in.	-	0.0002 in.

Wire cleaned in caustic soda and nitric acid, zincate treated, flashed with copper plating, and electroplated with zinc and cadmium as indicated.

TABLE V

SURFACE RESISTANCE VALUES FOR
PLATED AND BARE 2319 ELECTRODE

Filler Alloy	Plating	Mean Wire Surface Resistance (Microhm)*	Standard Deviation (Microhm)*	Avg Potential Drop (V)**
2319	None	24.1	3.64	.15
H	.0001 in. Zn	60.2	14.8	.35
I	.0001 in. Cd	-	-	.30

*Determined with surface resistance measuring apparatus reported under Task Order M-ME-TLA-AL-3

**Measured average voltage drop between contact tube and welding electrode.

TABLE VI
 WELD CRACK SENSITIVITY OF
2319 TYPE WELDING ELECTRODES WITH 2219 PLATE

<u>Filler Alloy</u>	<u>In. of Weld Cracking*</u>		<u>Sensitivity Rating</u>
	<u>Cont. Test</u>	<u>Disc. Test</u>	
2319	0	3-1/2	A
J M788(.27 Zn)	-	1/2	A
K M789(1.0 Zn)	-	1/2	A
L (.23 Cd)	-	1/2	A
M (0.12 Mg)	-	2-3/4	A
N (0.53 Mg)	-	16-3/4	C
O (.20 Ca)	0	11	B
P (.10 Ti, .01 V, .10 Zr)	0	13-1/4	C
Q (.09 Ti, .00 V, .00 Zr)	0	16-1/4	C

*Duplicate tests agreed within ± 1 inch from reported average values.

TABLE VII

PROPERTIES OF MIG WELDS IN 1/2-IN. 2219-T87 PLATE
WITH 1/16-IN. DIAMETER EXPERIMENTAL 2319 TYPE ELECTRODES

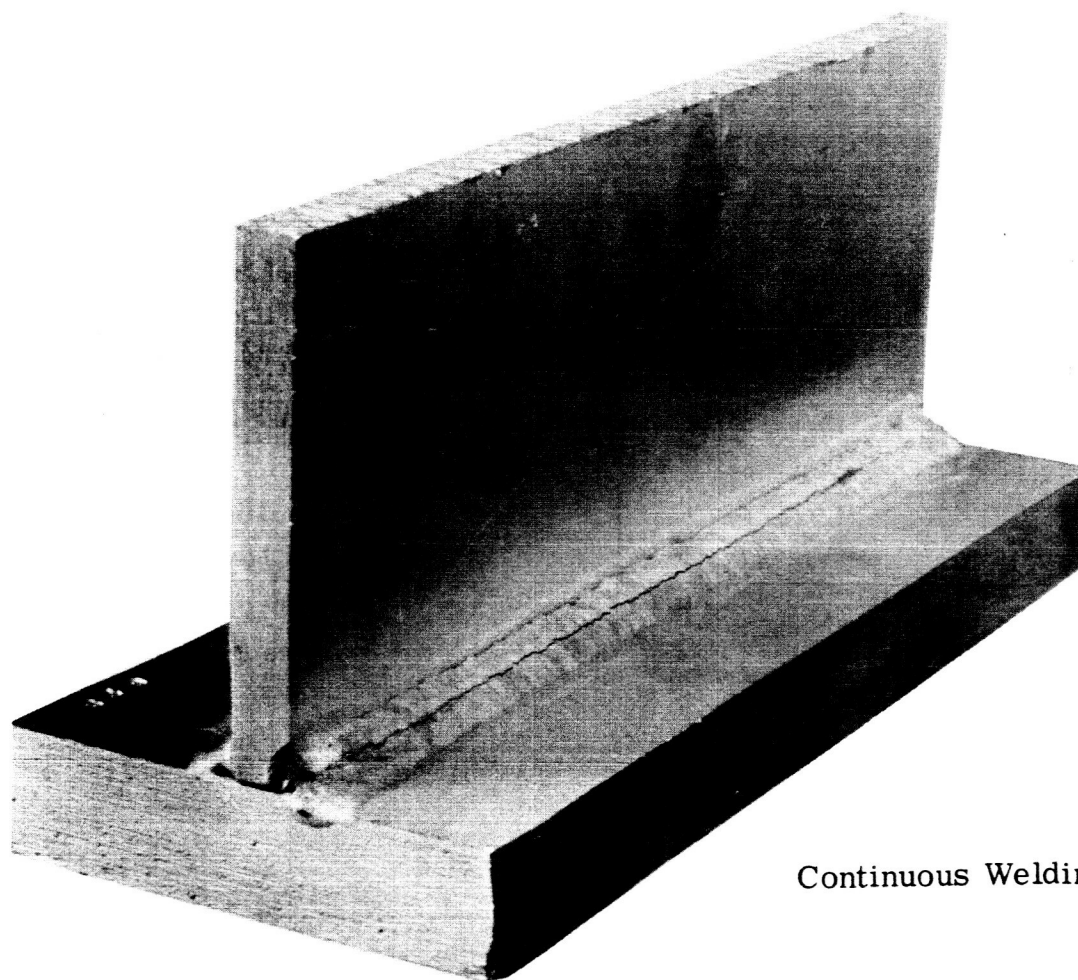
Filler Alloy	Welding Conditions*		Tensile Test Data**				
			Bead On		% El 2 in. 10 in.		Bead Off
			TS (psi)	YS (psi)			TS (psi)
2319 (6.2 Cu)	23.0	275	42,180	-	5.2	1.1	40,580
J (6.4 Cu-.27 Zn)	22.5	290	39,850	36,300	4.8	1.0	36,720
K (6.4 Cu-1.0 Zn)	23.0	290	42,080	35,200	6.0	1.2	38,320
L (6.3 Cu-.23 Cd)	23.0	285	41,180	36,050	5.2	1.0	38,000

*Welded in flat position, one pass from each side, employing 60° double V joint with 1/16-in. land, 16 to 20 ipm travel speed. X-ray examination revealed Class I or II soundness.

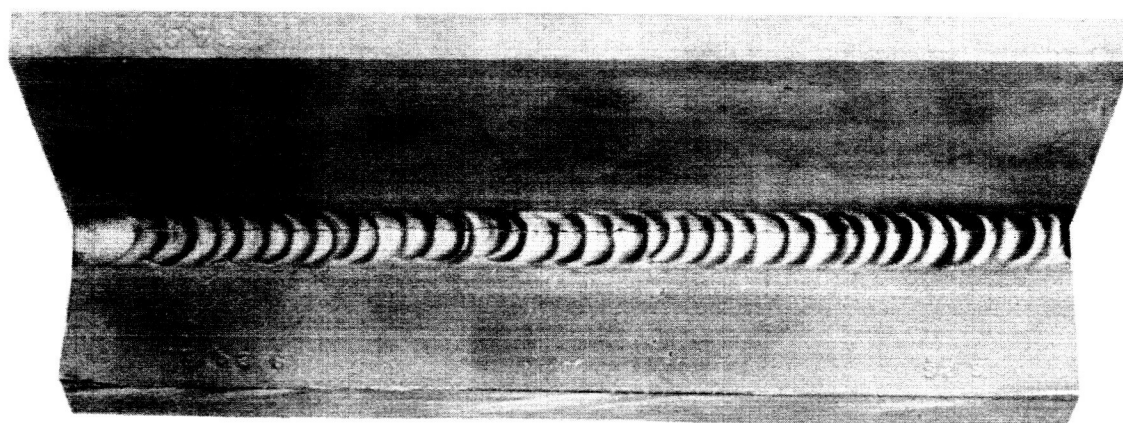
**Average of four tests varied within + 1000 psi except filler J, which varied within + 2000 psi. Failures occurred either at the weld-base metal interface or in the weld metal.



Figure 1 - Welding set up for examining Arc characteristics of aluminum electrodes



Continuous Welding Procedure



Discontinuous Welding Procedure

Figure 2 - Alcoa T-Joint weld cracking specimen

[illegible]

FIG.3 WELD TENSILE TEST SPECIMENS

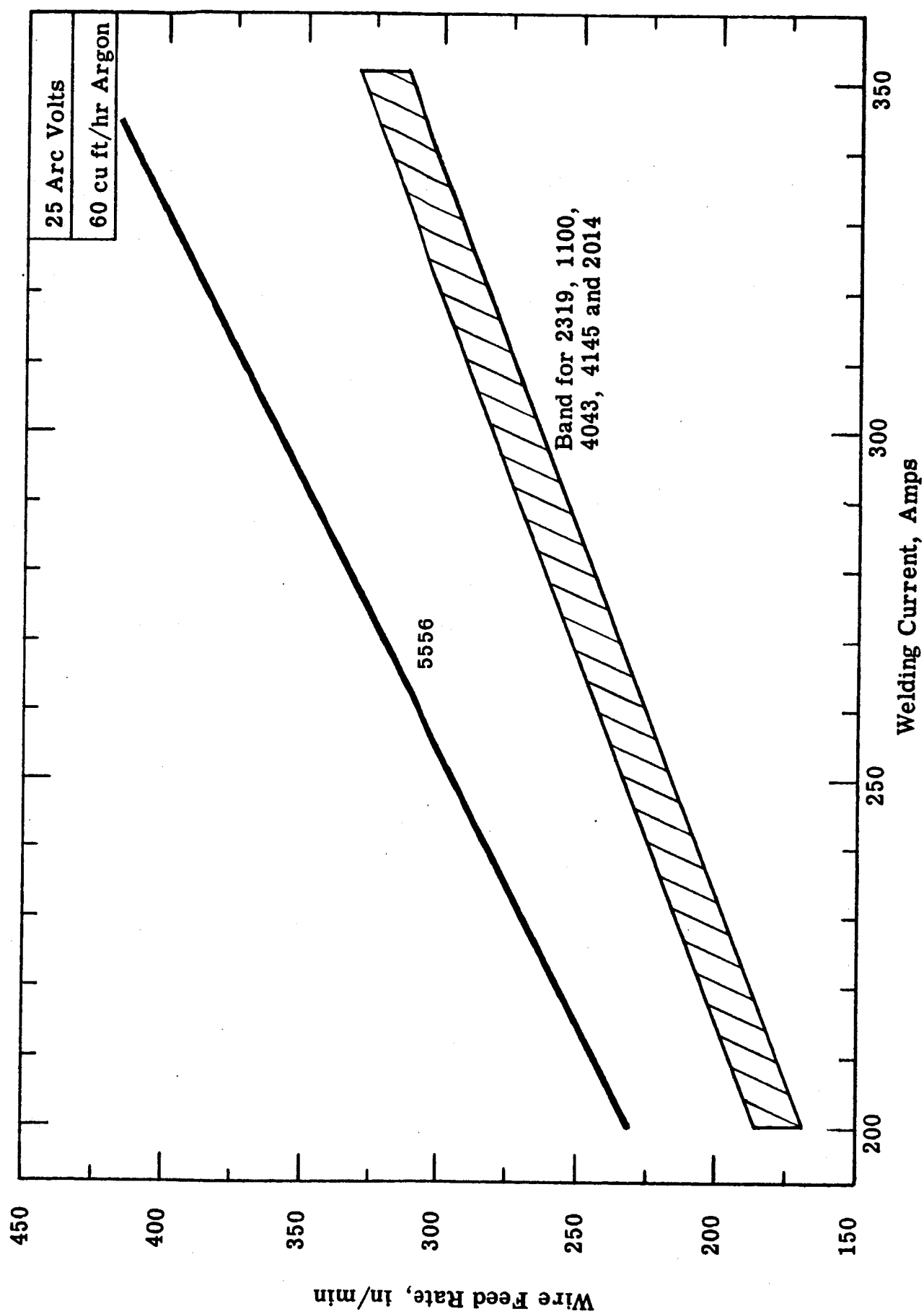


Fig. 4 - Melt-Off Rates for 1/16 in. diameter Standard Aluminum Electrodes

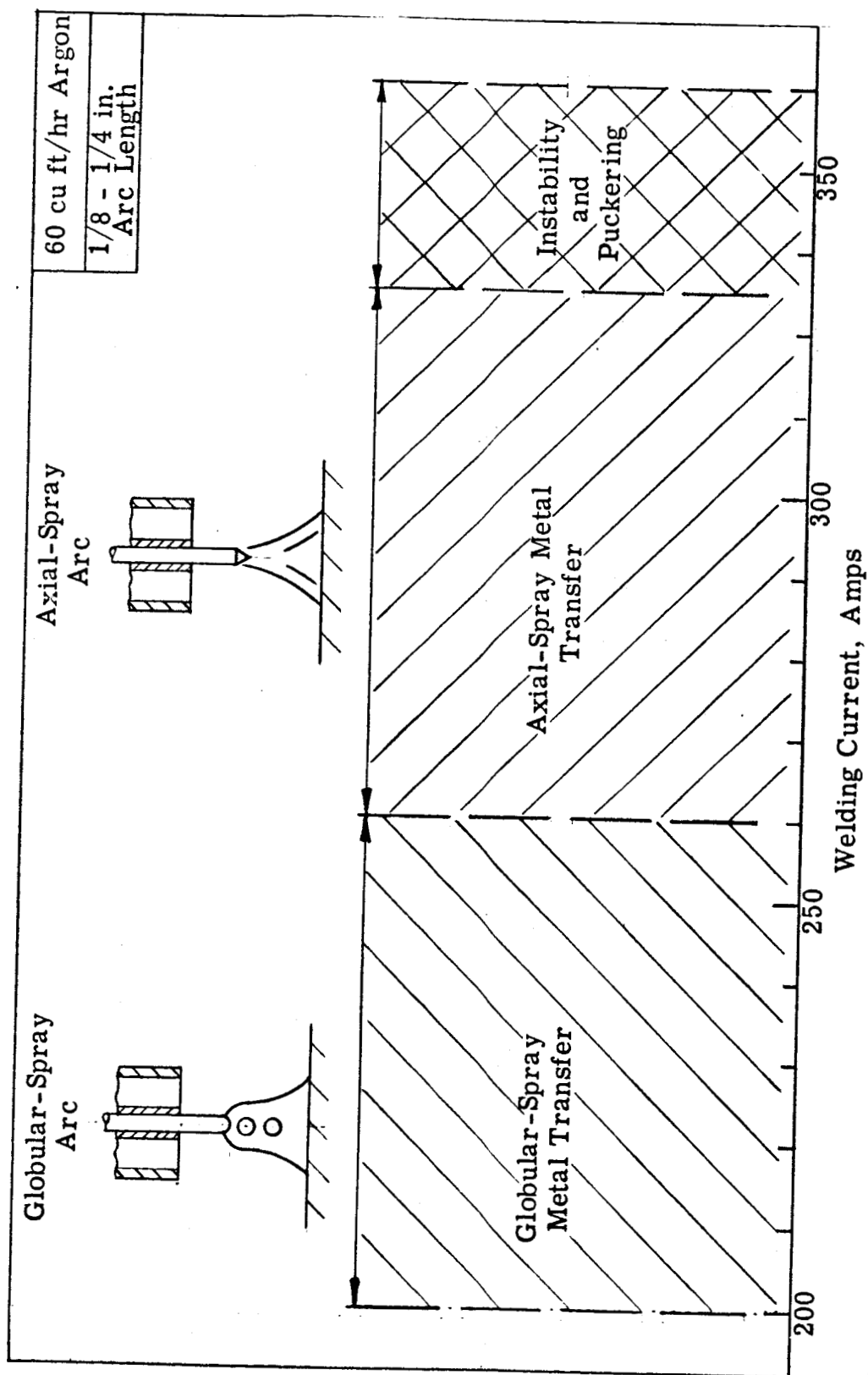


Fig. 5 - Metal Transfer Characteristics for 1/16 in. diameter Standard Aluminum Electrodes (Alloys 2319, 1100, 5556, 2014, 4043 and 4145)

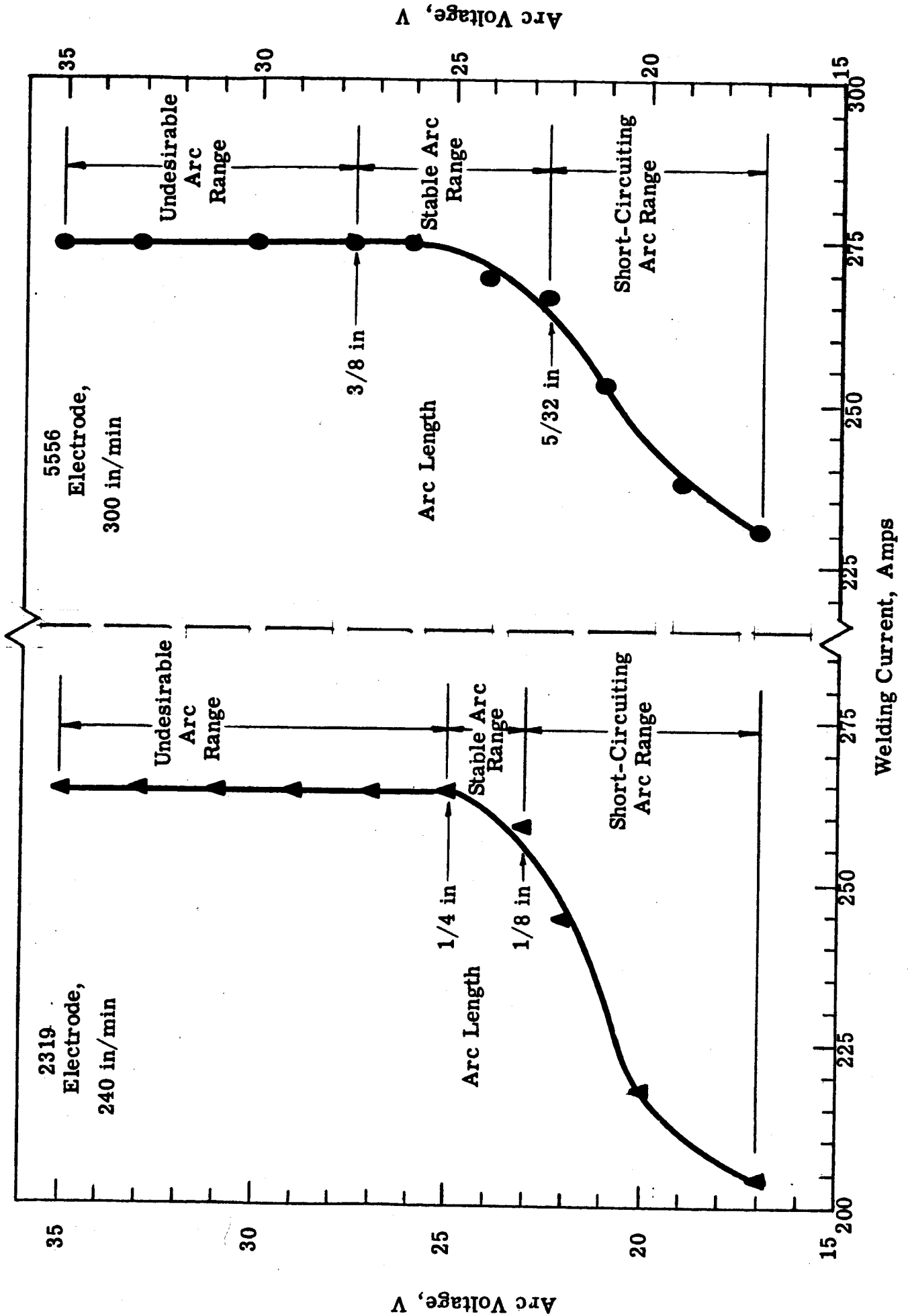


Fig. 6 - Arc Stability for 1/16 in diameter 2319 and 5556 Electrodes

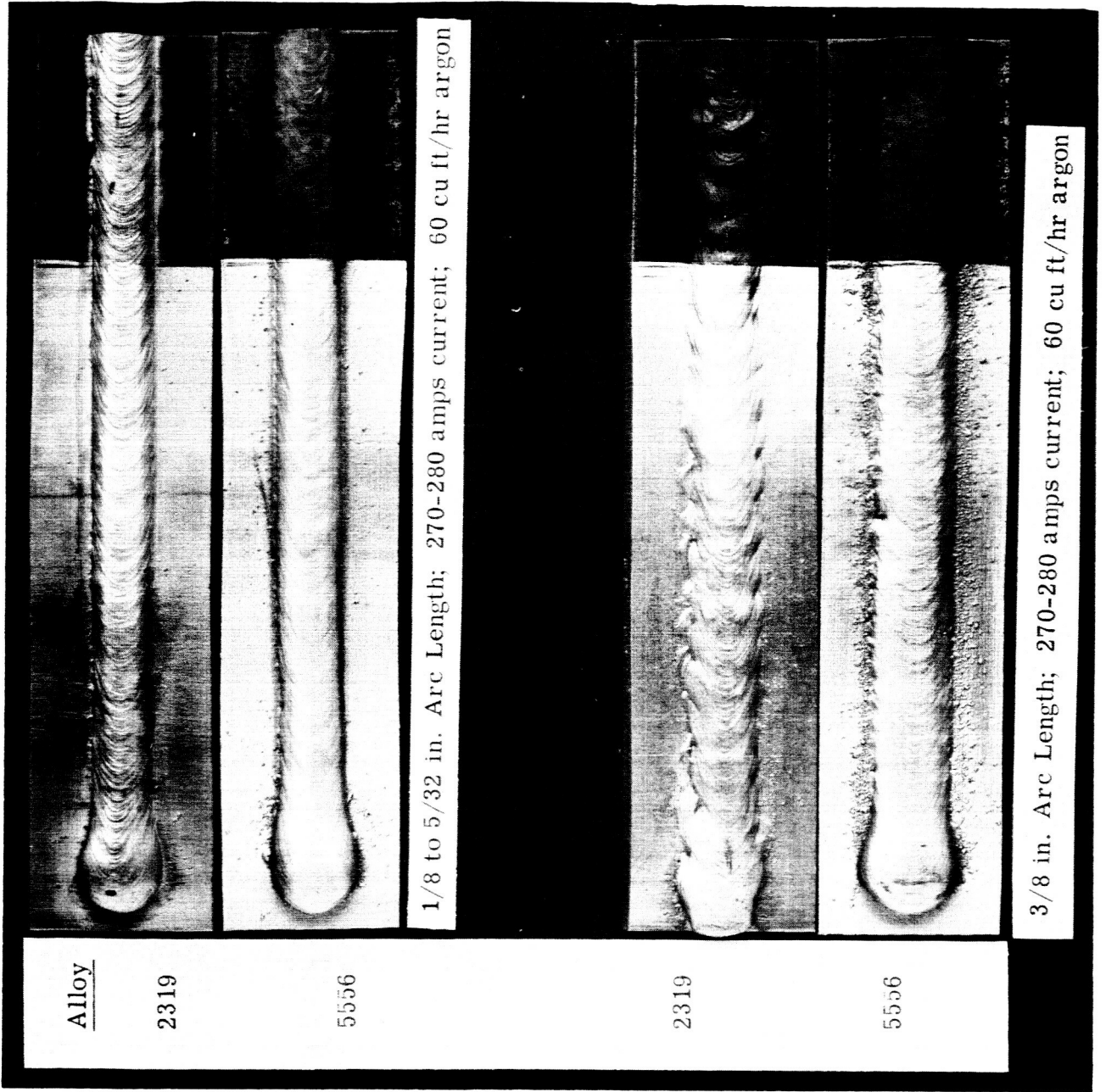


Figure 7 - Photograph of weld beads deposited with 2319 and 5556 electrodes

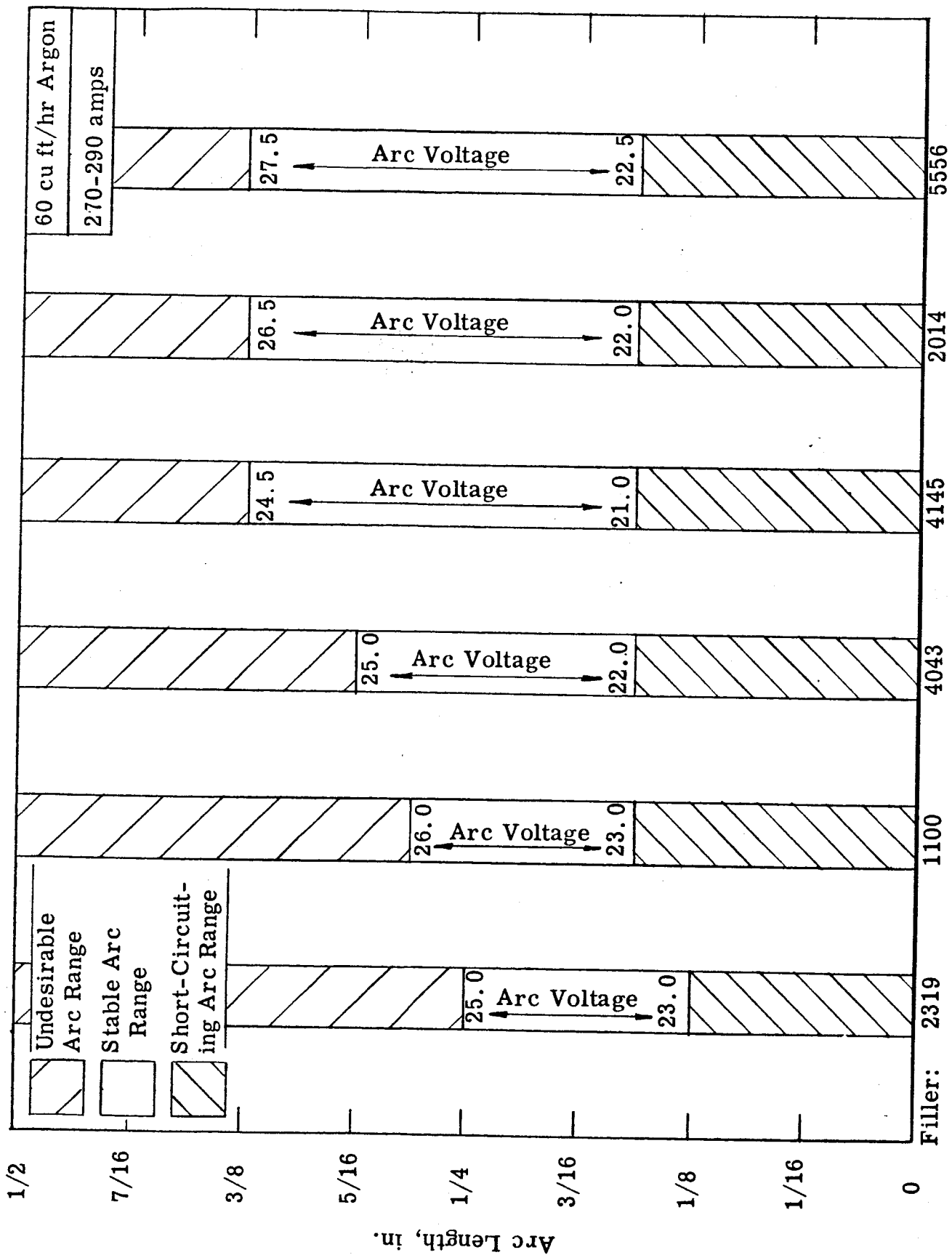


Fig. 8 - Arc Stability for 1/16 in. diameter 2319, 1100, 4043, 4145, 2014 and 5556 Electrodes.

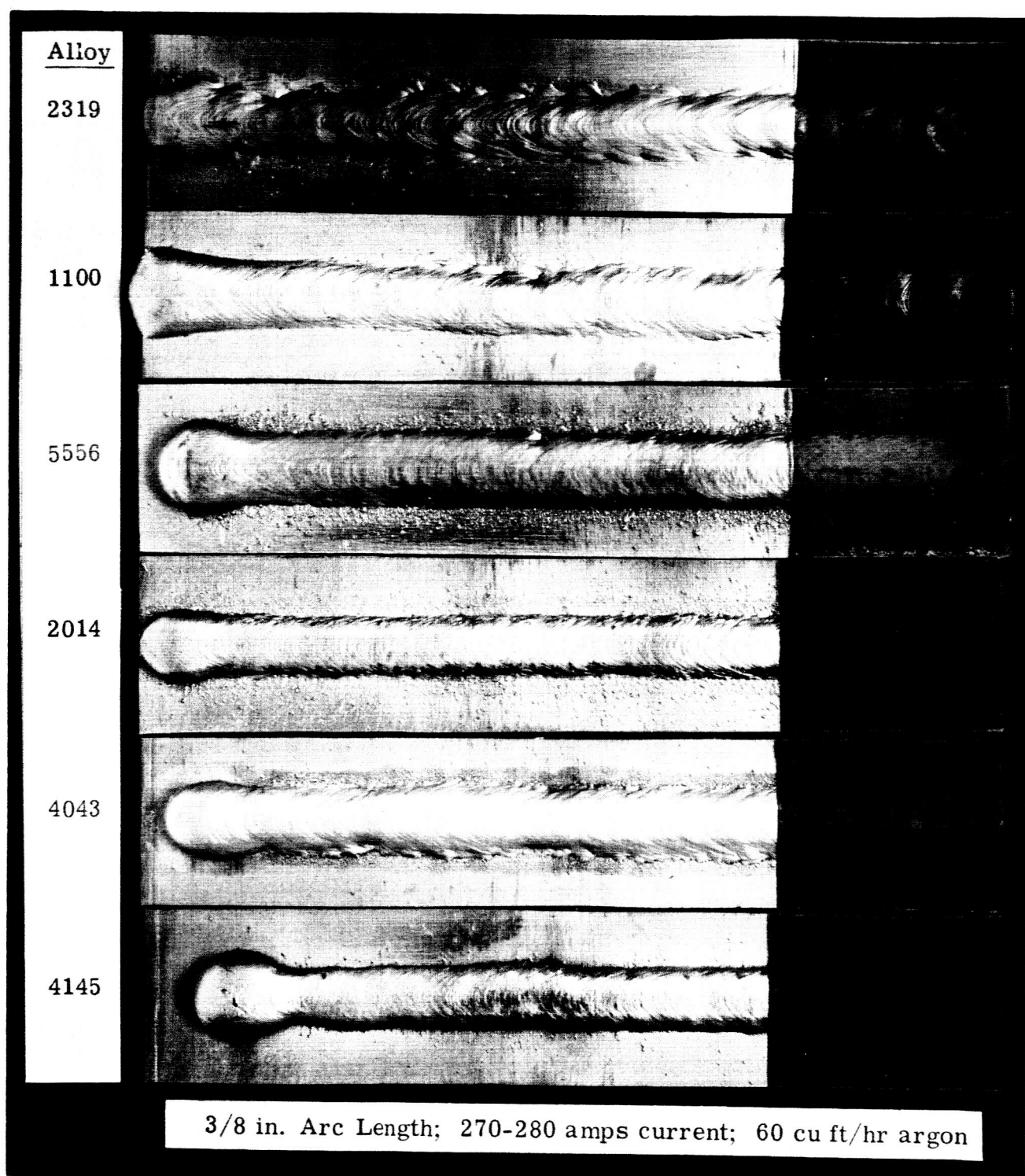


Figure 9 - Photograph of weld beads deposited by 2319, 1100, 5556, 2014, 4043 and 4145 electrodes

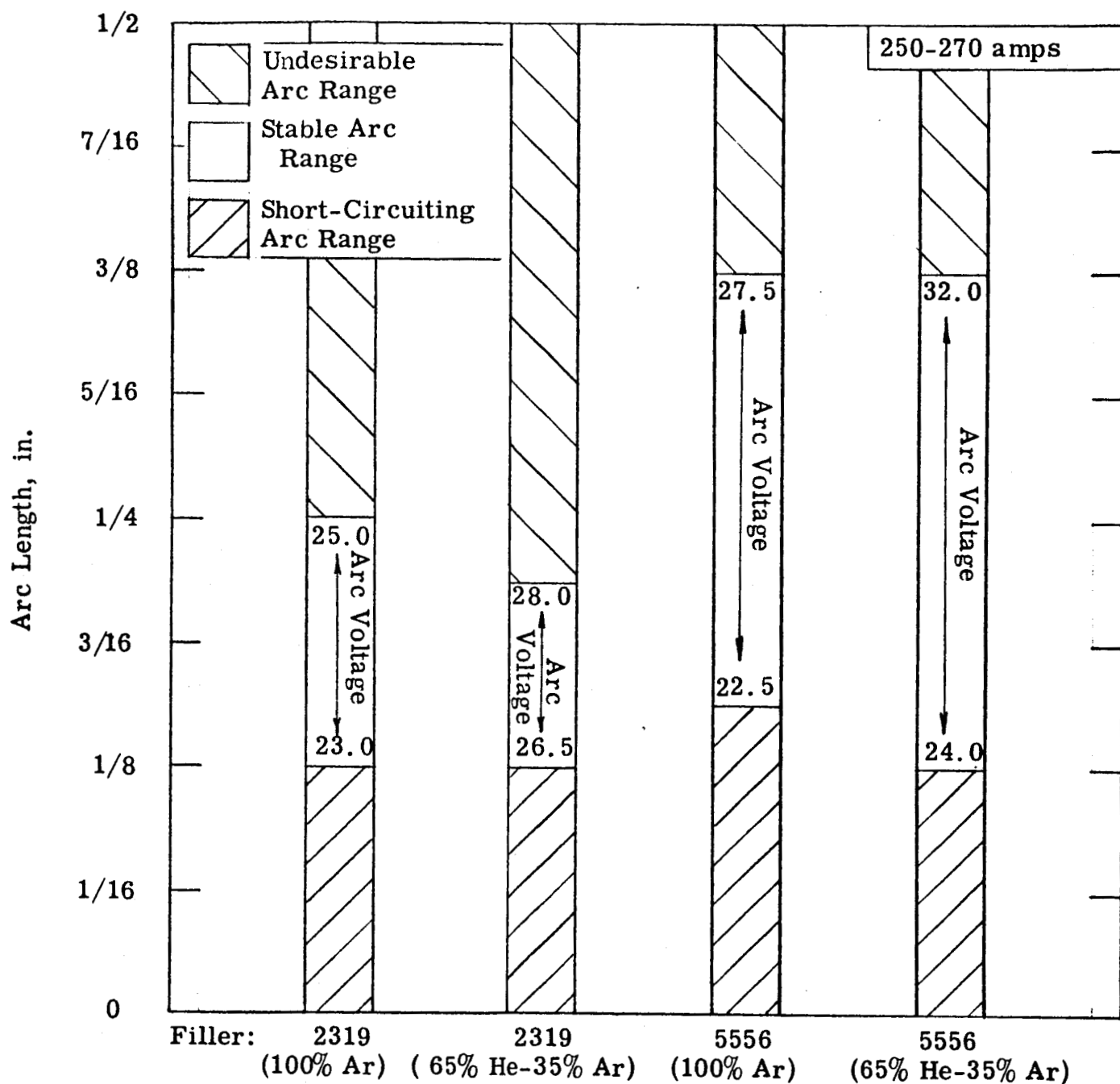
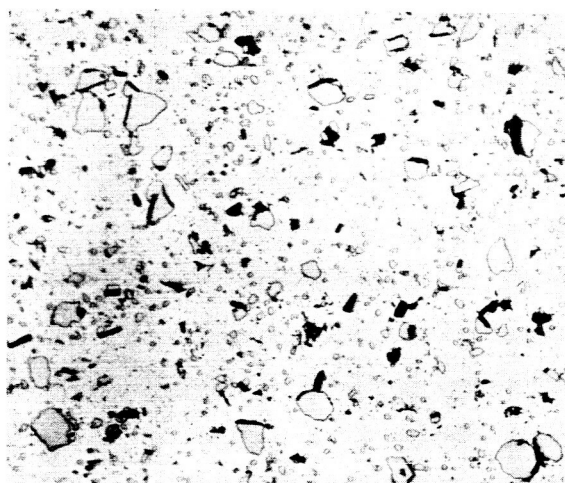
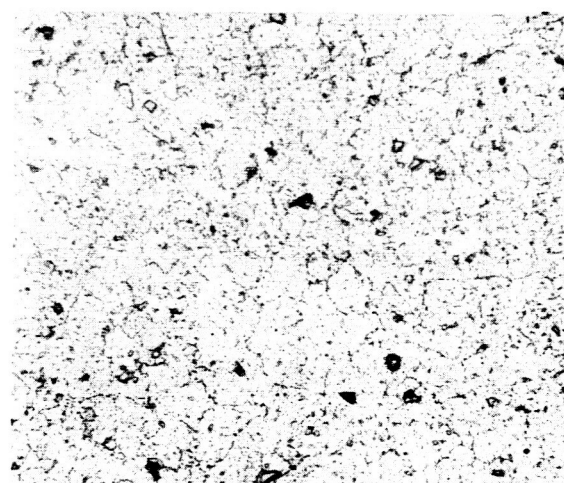


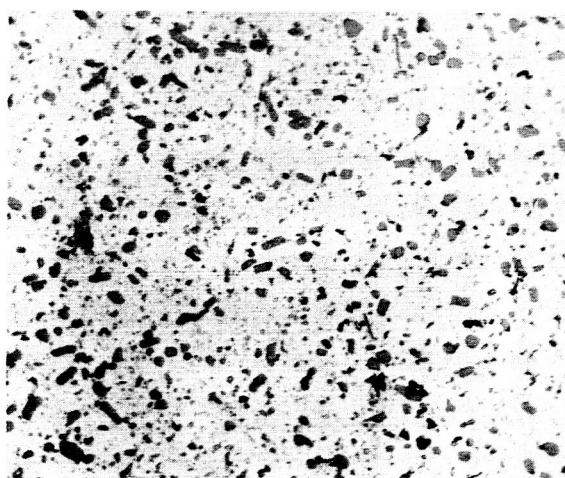
Fig. 10 - Arc Stability for 1/16 in. diameter 2319 and 5556 Electrodes with 100% Ar and 65% He-35% Ar Shielding Gases



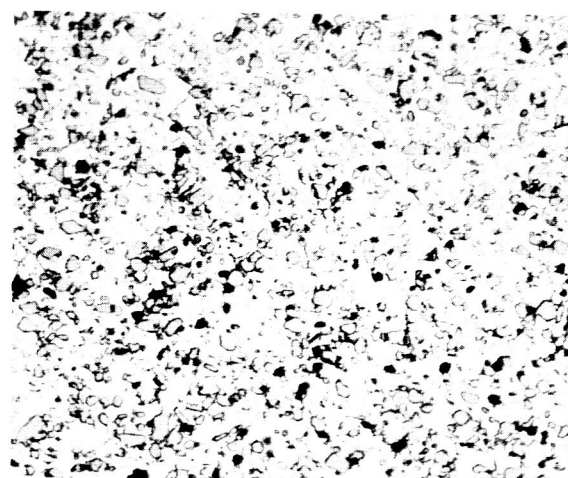
500X Keller's Etch
2319 Electrode



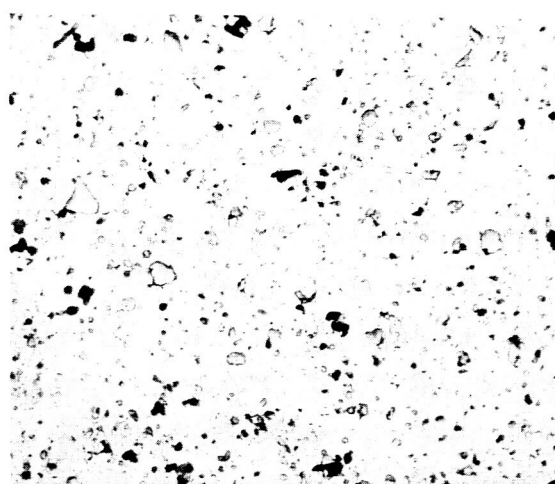
500X Keller's Etch
5556 Electrode



500X Keller's Etch
4043 Electrode



500X Keller's Etch
4145 Electrode



500X Keller's Etch
2014 Electrode

Figure 11 - Cross section microstructures of 1/16 in. diameter aluminum alloy electrodes in the as fabricated condition.

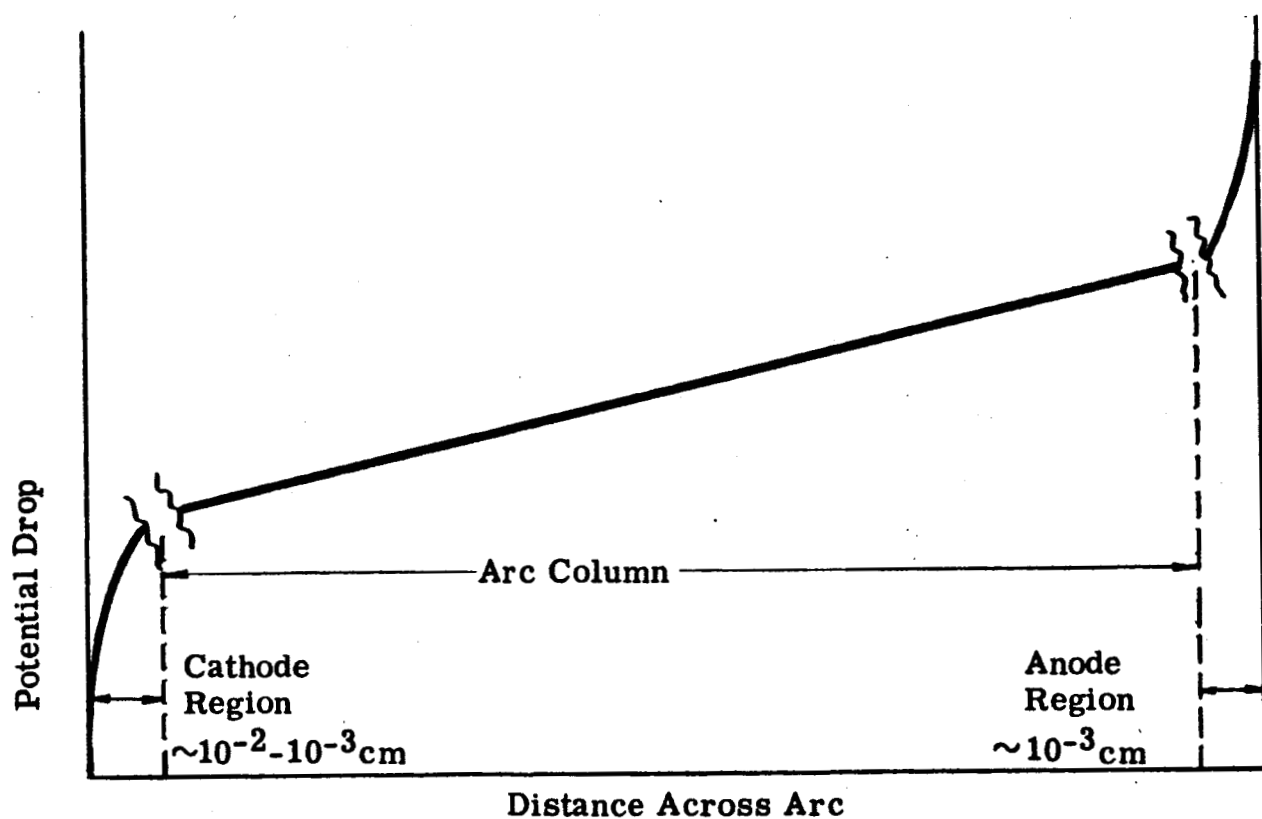


Fig. 12a - Diagrammatic Representation of Potential Distribution Across a Direct Current Arc⁷

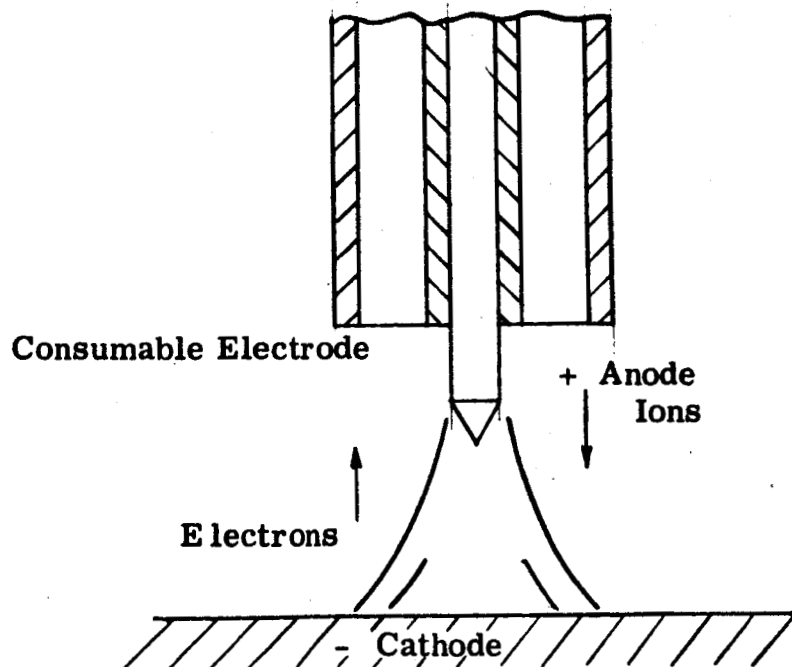
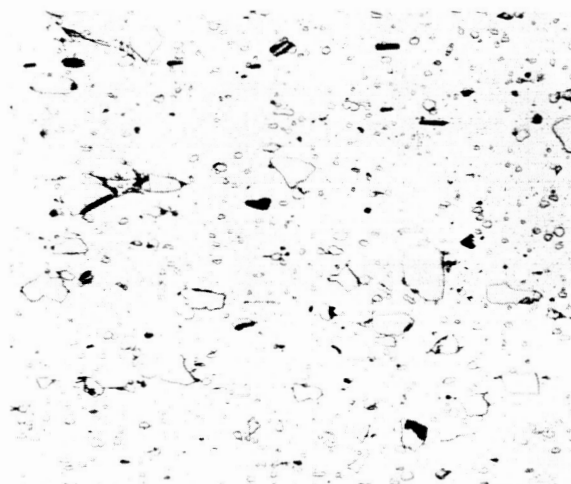


Fig. 12b - Illustrates Charge Carrier Flow of Direct Current Reverse Polarity (Electrode Positive) Welding Arc



100X

Unetched

500X

Keller's Etch

2319 Electrode - XXXXXXXXXX *As Fabricated*

Figure 13 - Longitudinal section microstructures of 1/16 in. diameter 2319 electrode in as fabricated and solution heat treated and aged conditions.

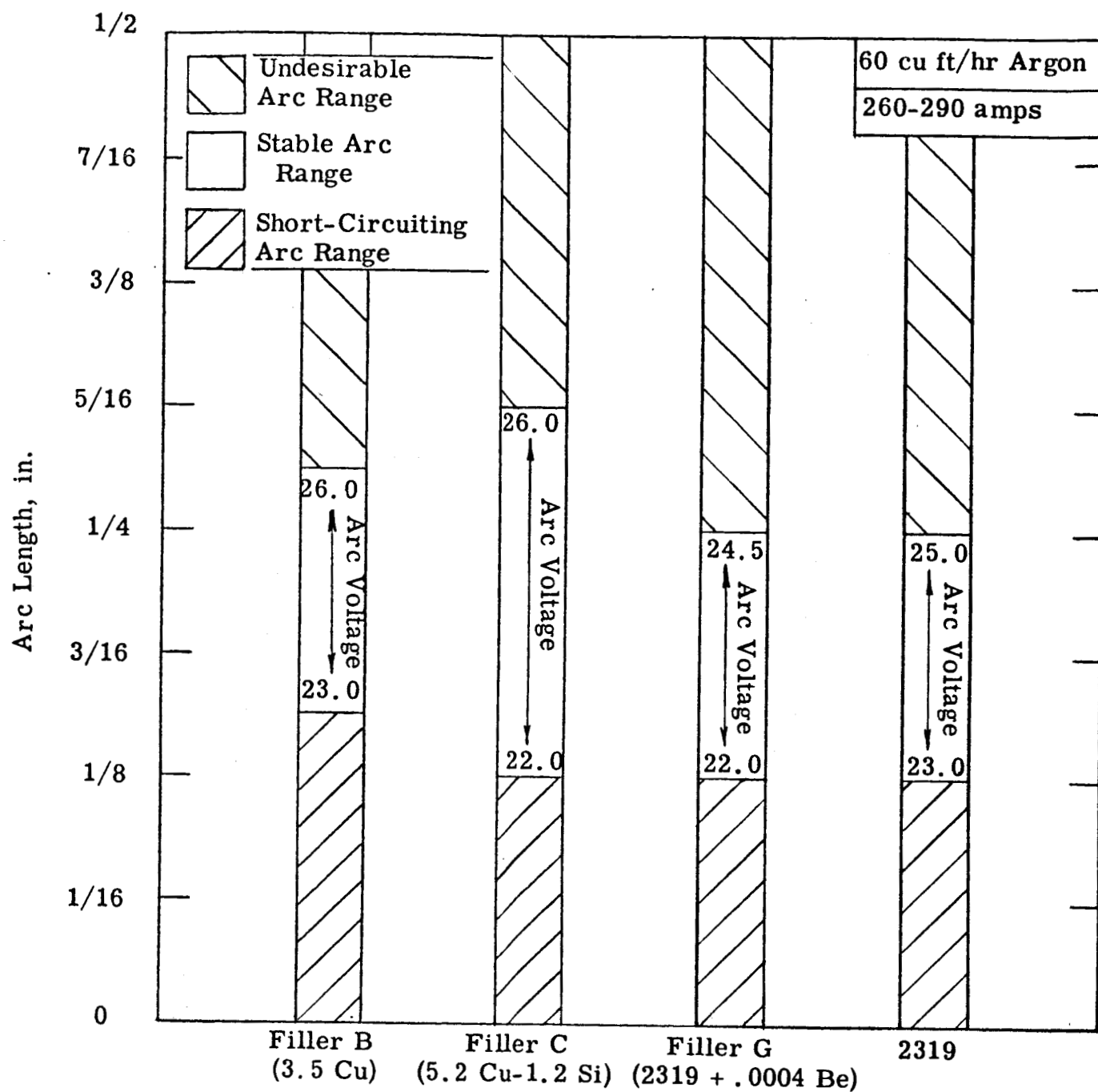
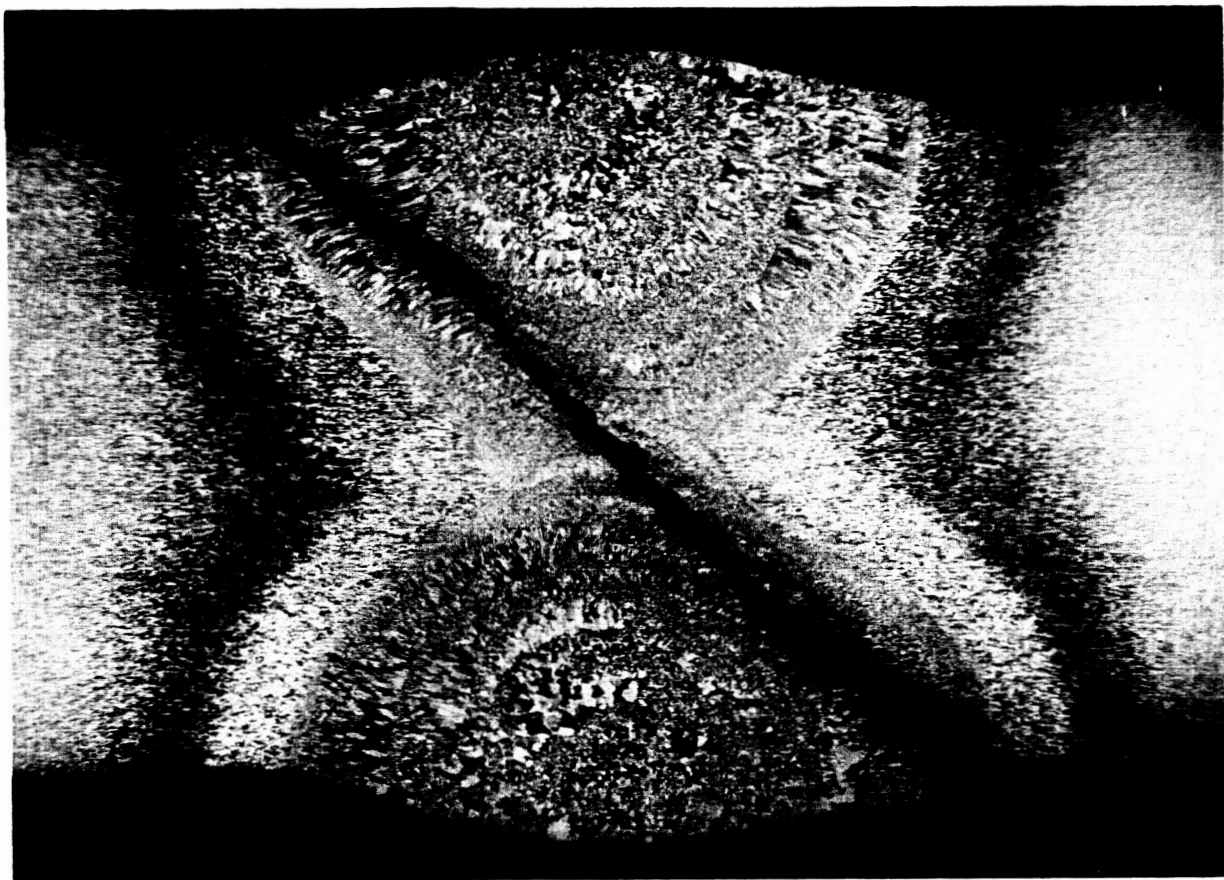


Fig. 14 - Arc Stability for 1/16 in. diameter Modified 2319-Type Electrodes (Cu, Si, Be)



8X

Keller's Etch

Figure 15 - Cross section of fractured 2 pass weld specimen in 1/2 in.
2219-T87 plate with Filler B (3.5% Cu)

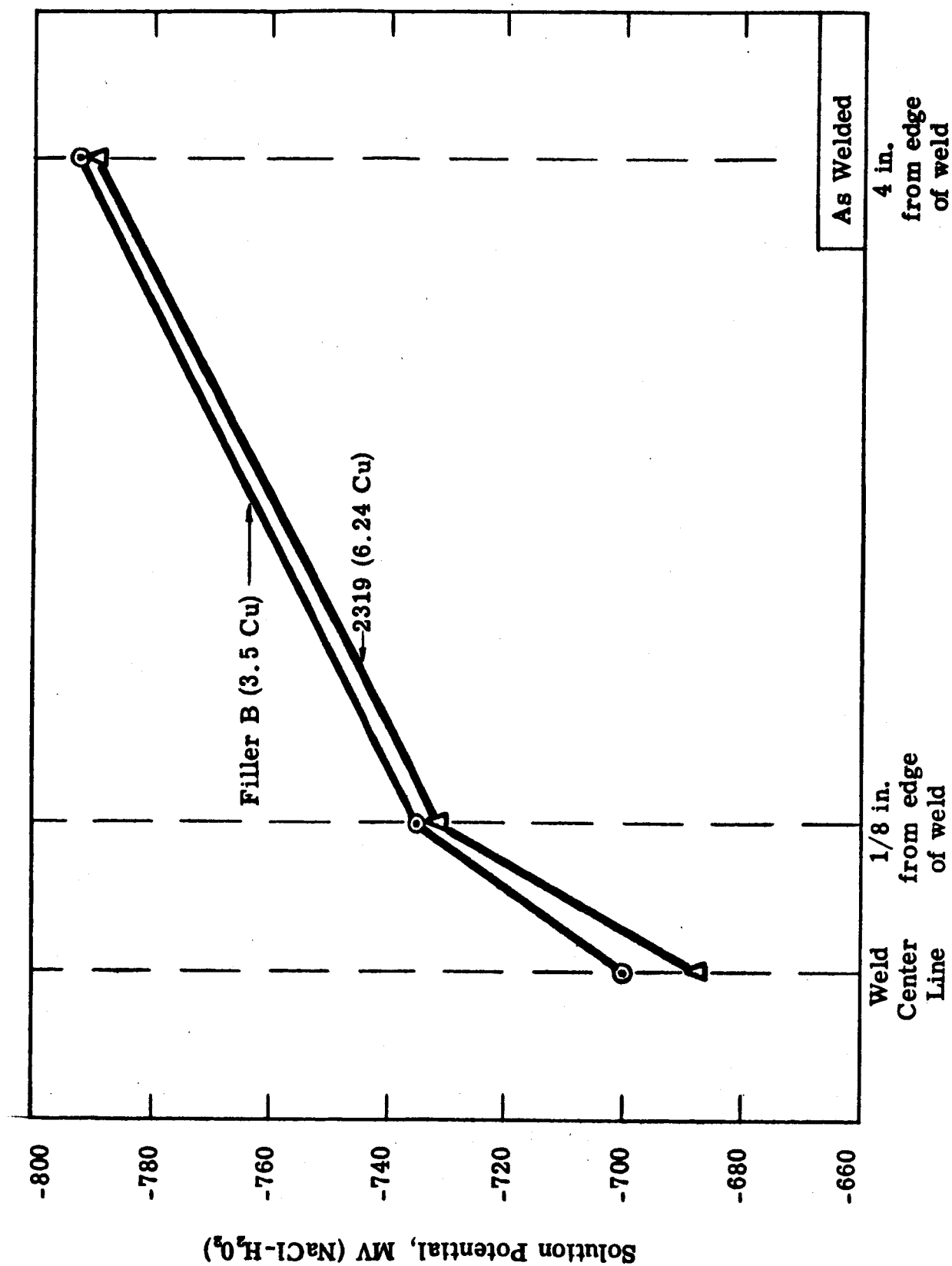


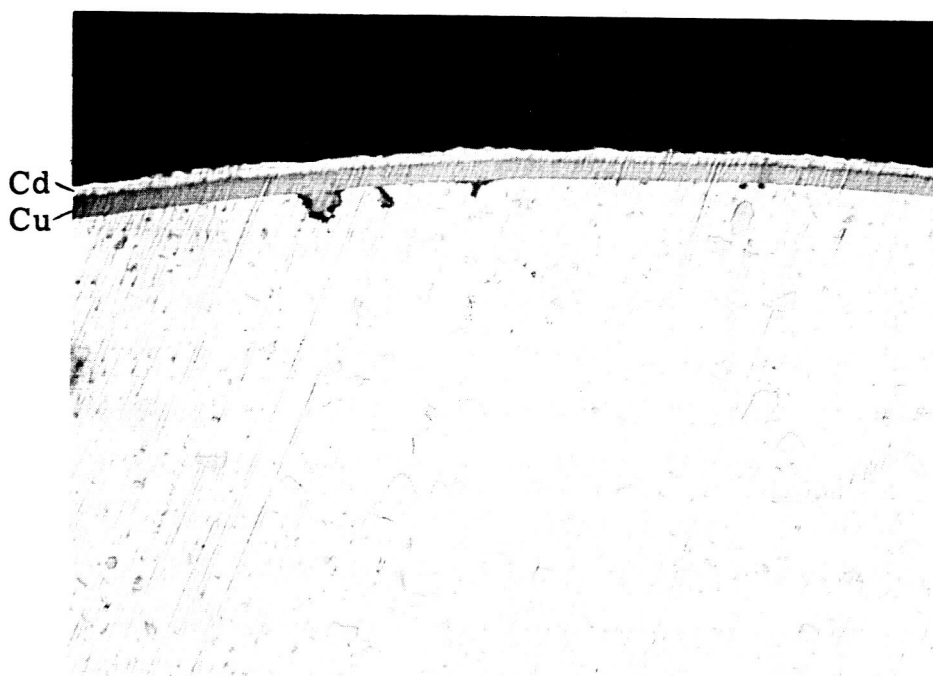
Fig. 16 - Solution Potential Data for Gas Metal Arc (MIG) Welds in 1/2 in. 2219-T87 Plate with Filler B (3.5 Cu) and 2319



Mag. 500X

Unetched

Figure 17a - Cross section of 1/16 in. 2319 electrode electroplated with Cu and Zn (5 min. Zn plating). Filler H



Mag. 500X

Unetched

Figure 17b - Cross section of 1/16 in. 2319 electrode electroplated with Cu and Cd (5 min. Cd plating). Filler I

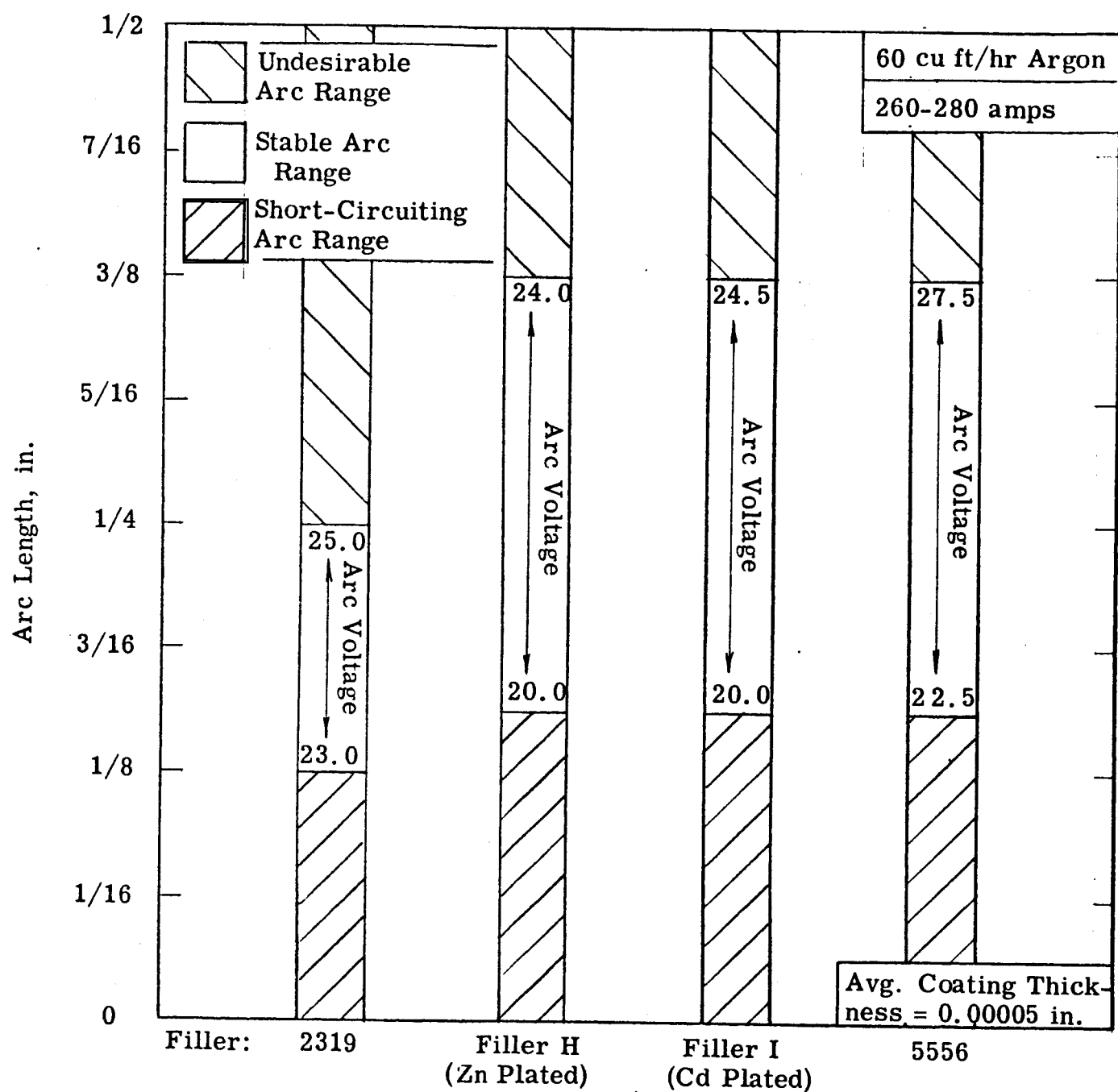


Fig. 18 - Arc Stability for Zn and Cd Plated 2319 Compared with Bare 2319 and 5556 Electrodes

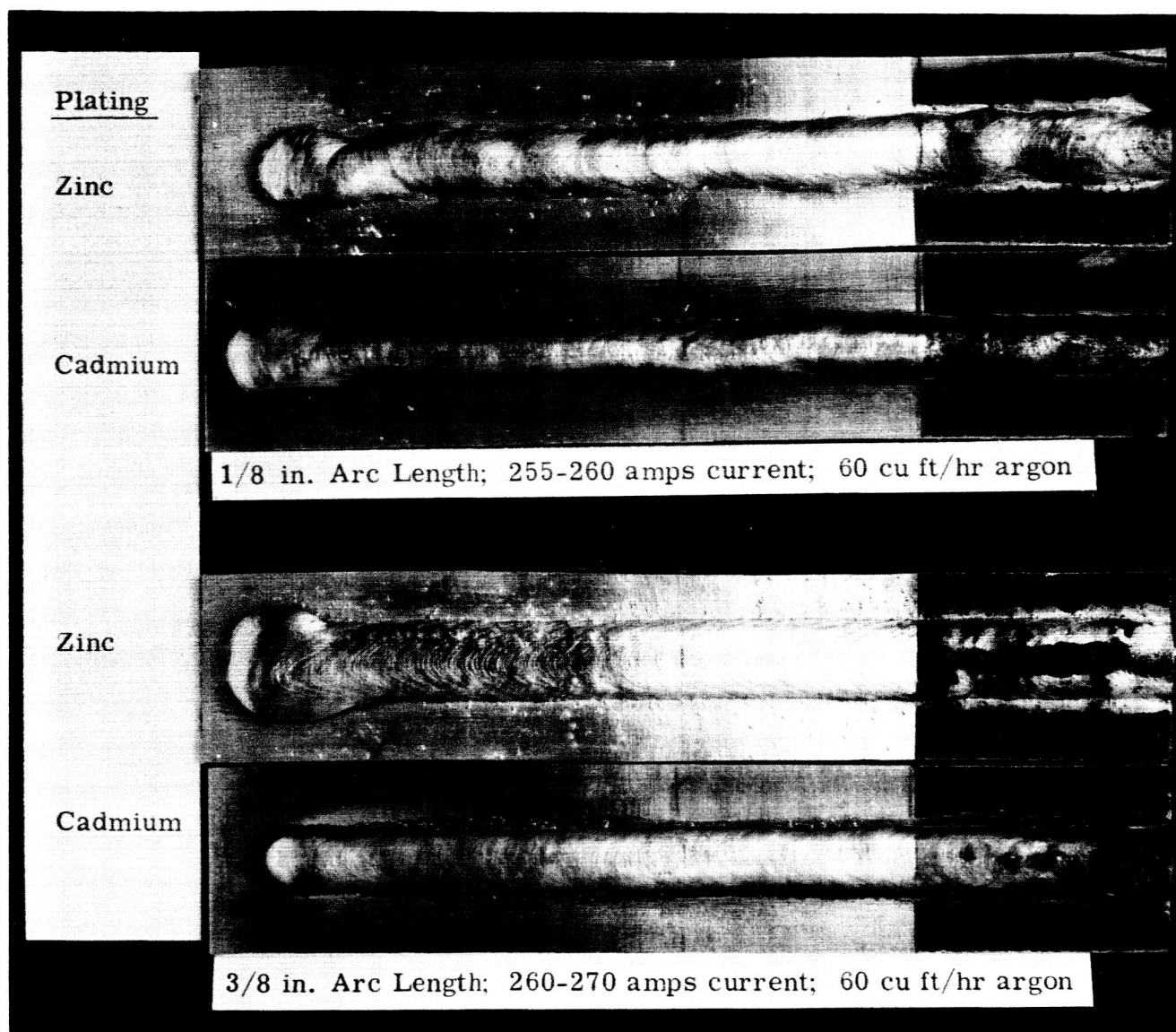


Figure 19 - Photograph of weld beads deposited by Zn and Cd coated 2319 electrode

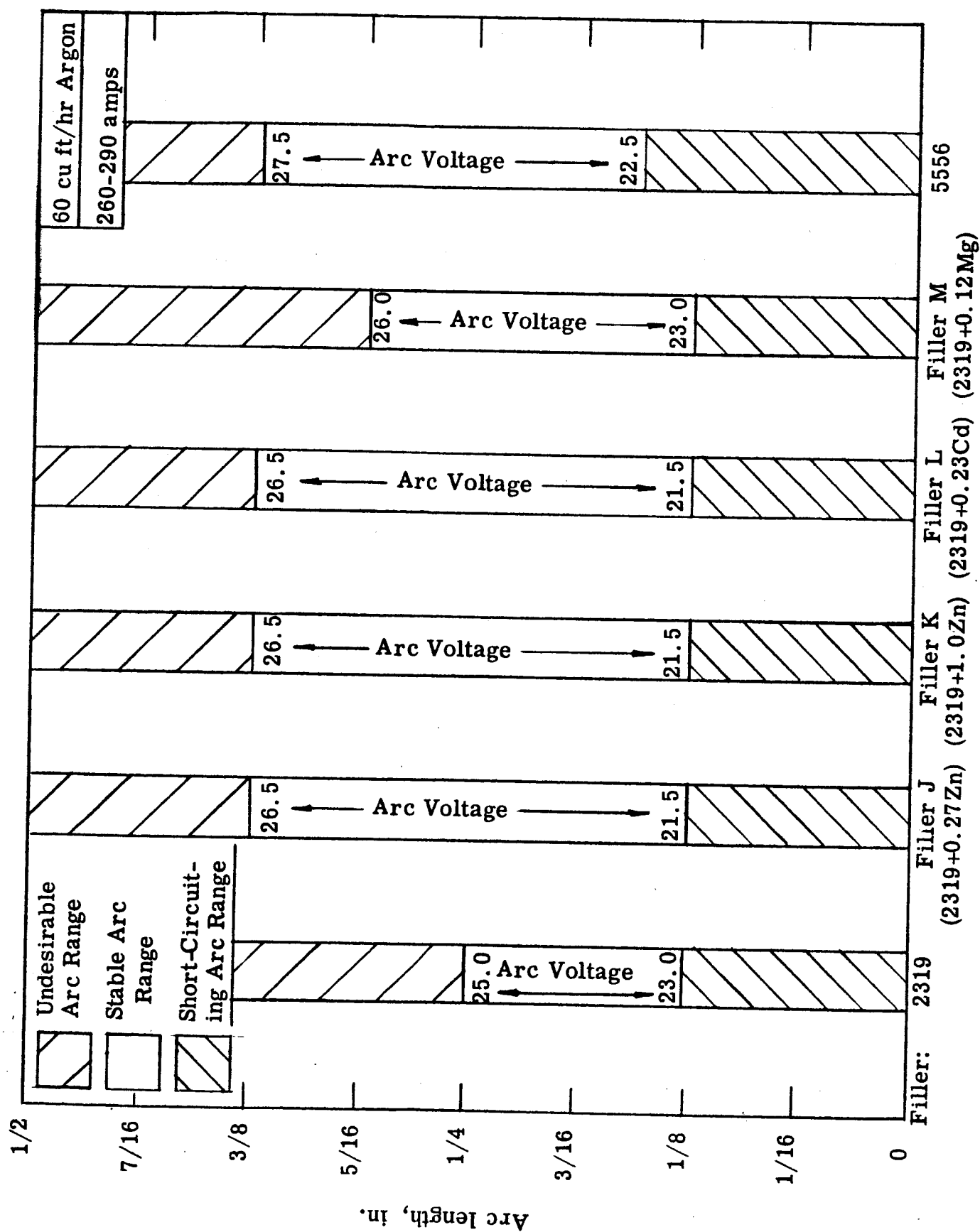
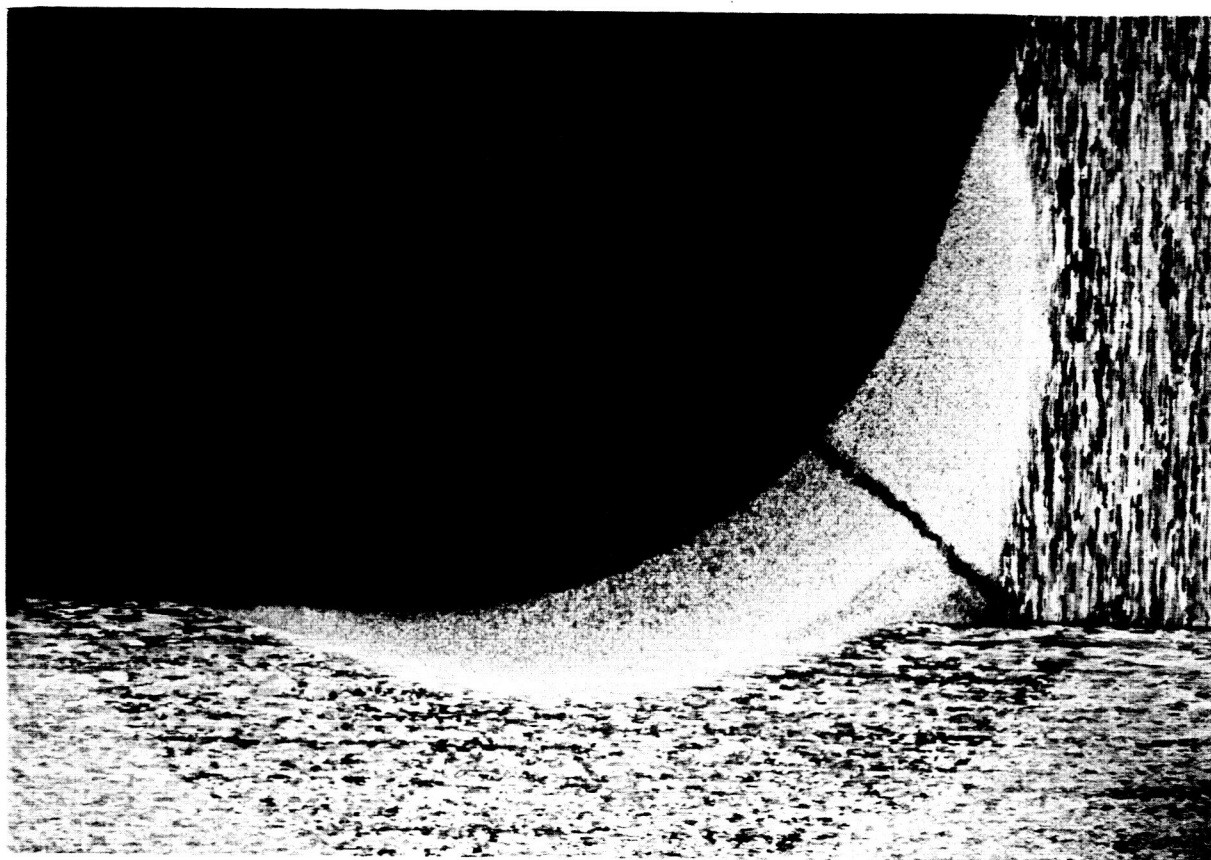


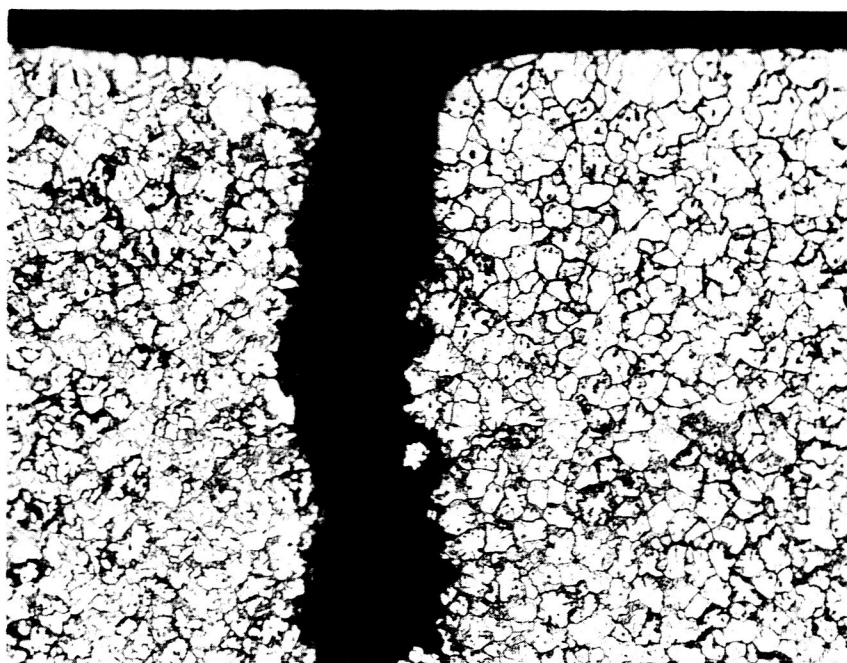
Fig. 20 - Arc Stability for 1/16 in. diameter Modified 2319-Type Electrodes (Zn, Cd, Mg)



Mag. 10X

Etch: Keller's

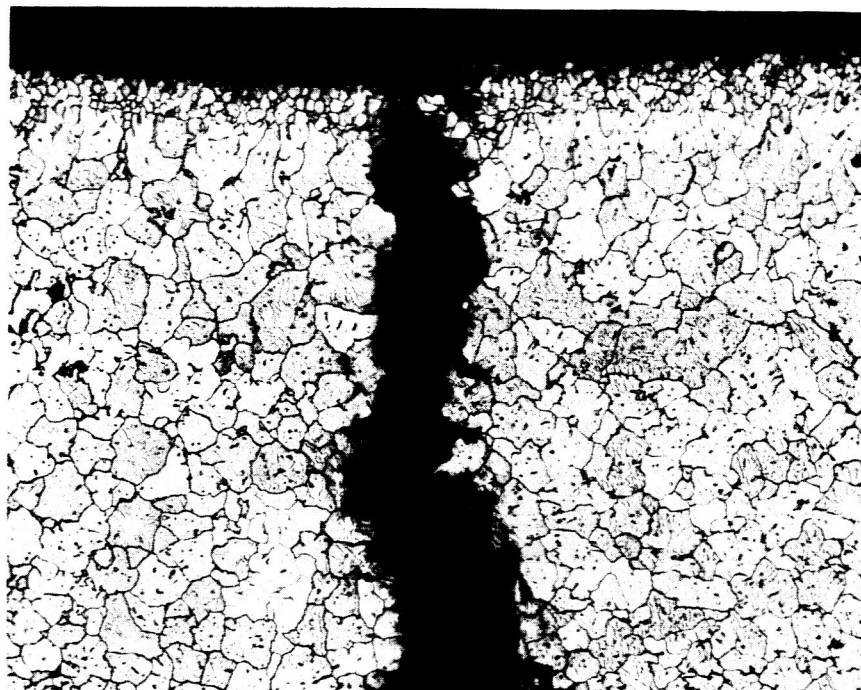
Figure 21a - Shows the weld region in 2219 plate welded with Filler K (2319 + 1.0 Zn). Specimen cracked 1/2 in.



Mag. 100X

Etch: Keller's

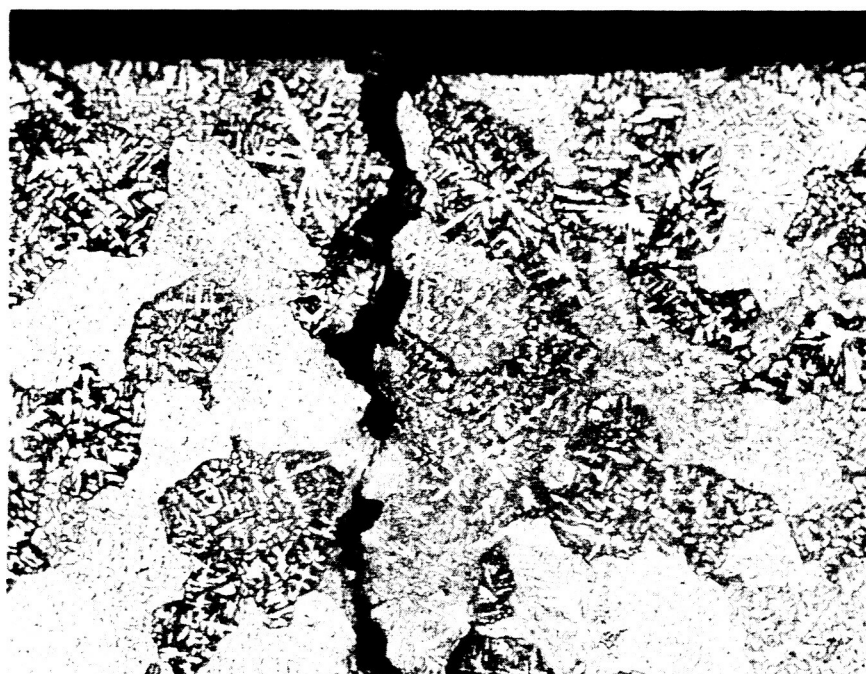
Figure 21b - Shows the grain size of the cracked region in the above specimen at higher magnification.



Mag. 100X

Etch: Keller's

Figure 22 - Shows the grain size of the cracked weld region in 2219 plate welded with 2319 filler. 3-1/2 inches of cracking occurred.



Mag. 100X

Etch: Keller's

Figure 23 - Shows the grain size of the cracked weld region in 2219 plate welded with Filler P (.10 Ti, .01 V, .10 Zr). 13-1/4 inches of cracking occurred.

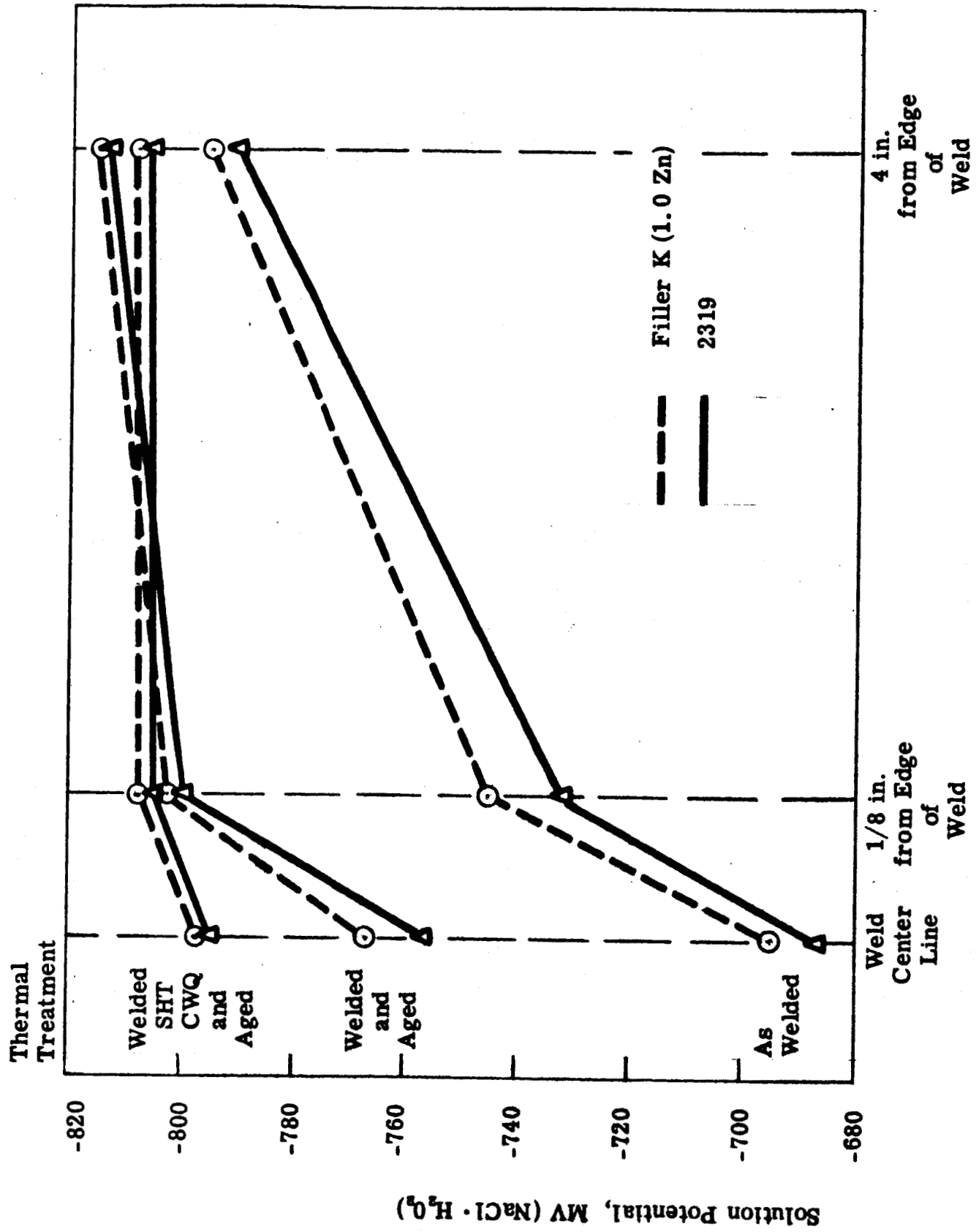


Fig. 24 - Solution Potential Data For Gas Metal Arc (MIG) Welds in 1/2 in. 2219 Plate with Filler K (1.0 Zn) and 2319

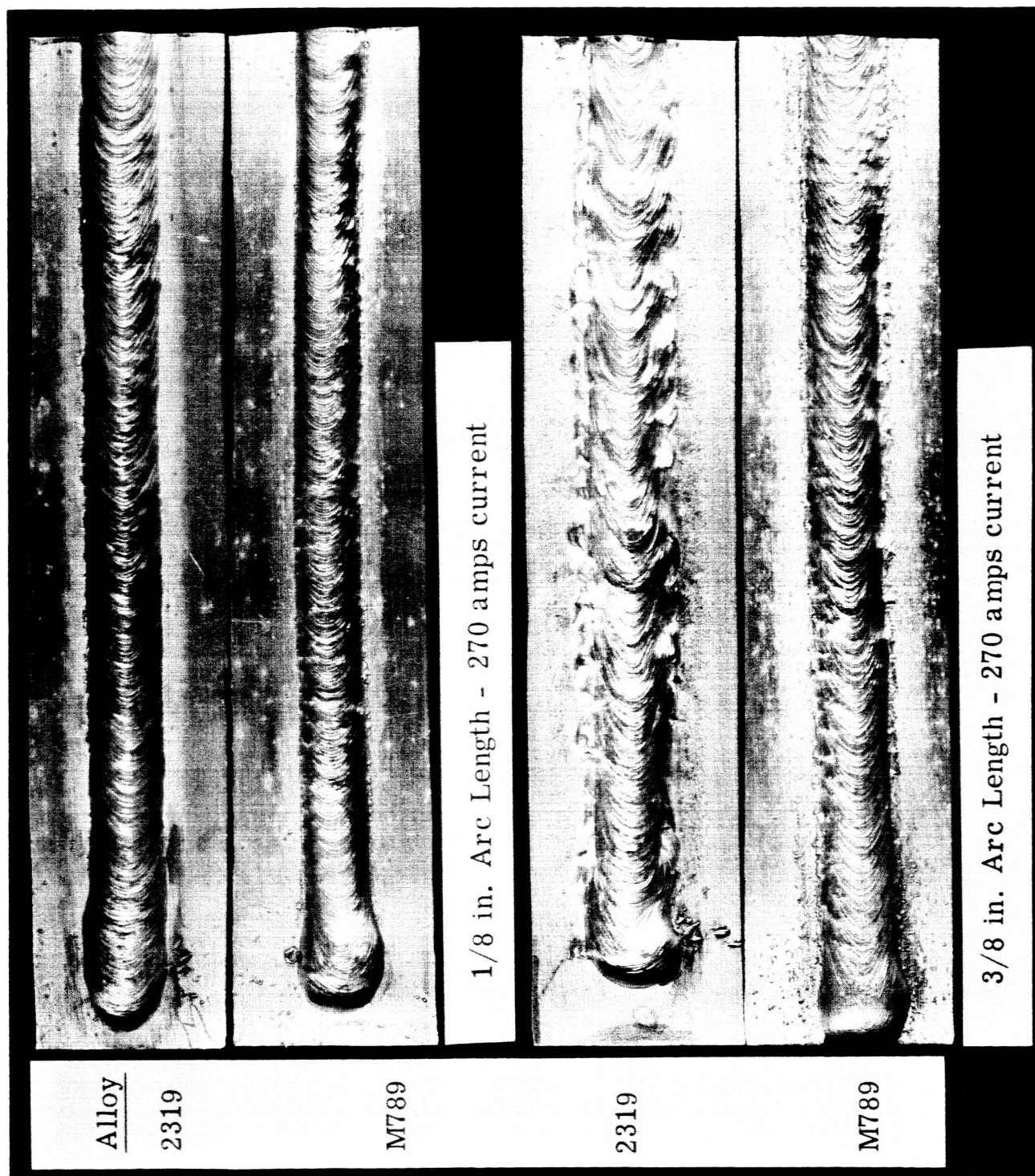


Figure 25 - Photograph of weld beads deposited by 2319 and M789 (2319 + 1.0 Zn) fillers in flat position

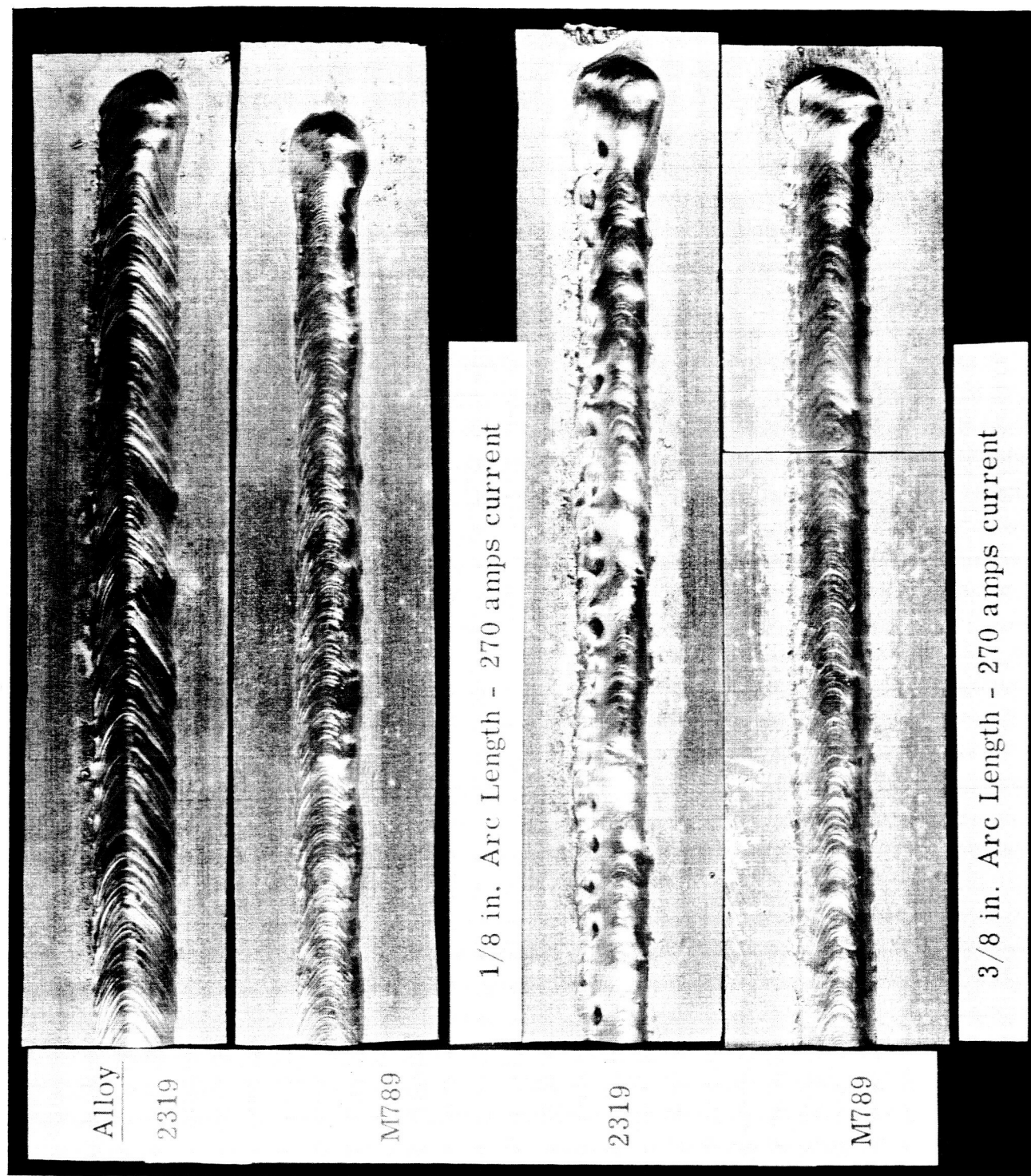


Figure 26 - Photograph of weld beads deposited by 2319 and M789 (2319 + 1.0 Zn) fillers in the horizontal position

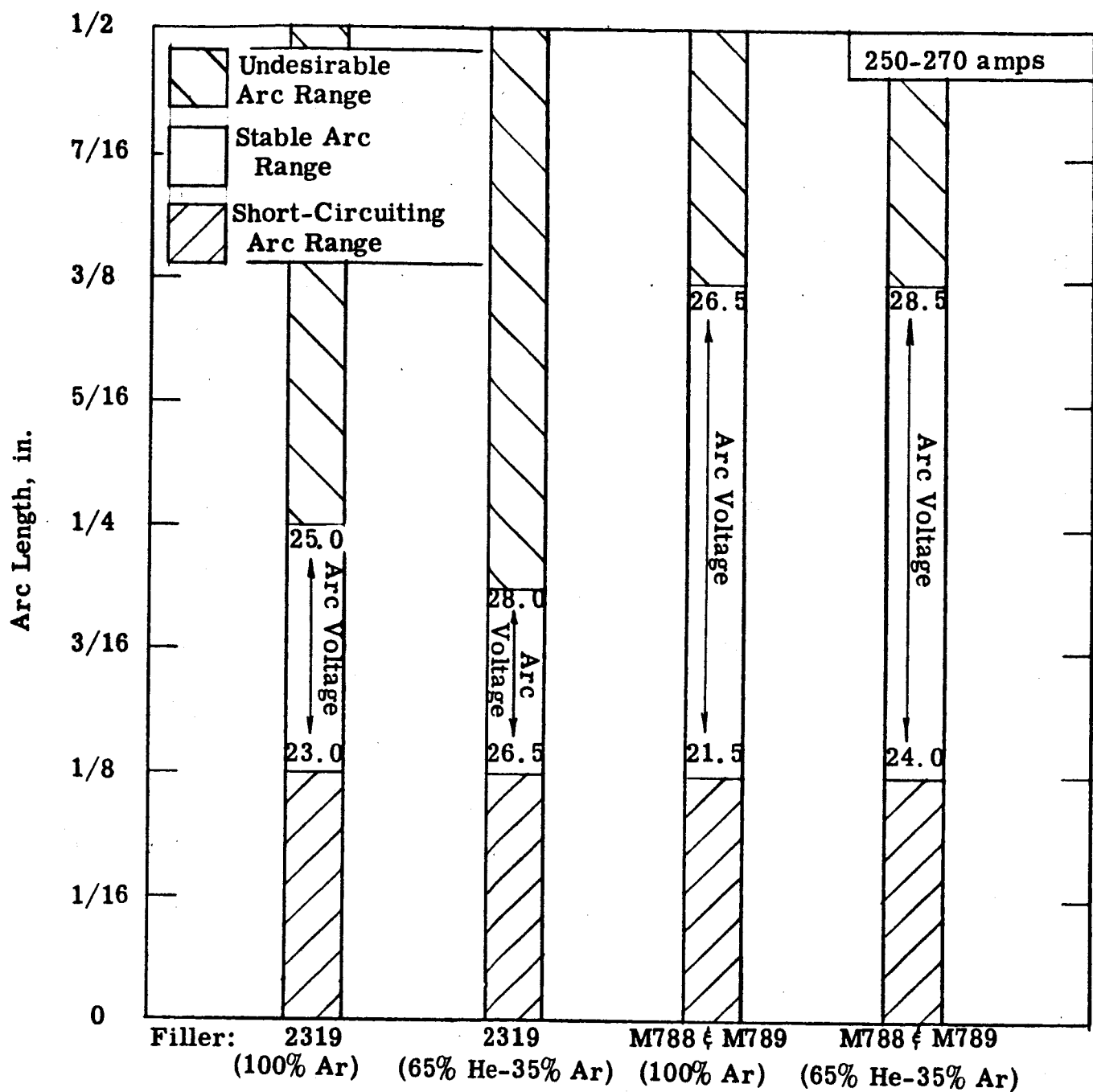


Fig. 27 - Arc Stability for 1/16 in. diameter 2319 and 2319+Zn Electrodes (M788 and M789) with 100% Ar and 65% He-35% Ar Shielding Gases.